

AD 634867

SECTION

T

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
8621 GEORGIA AVE. SILVER SPRING, MD.

Operating under Contract NOrd 7386
With the Bureau of Ordnance, U. S. Navy

A SUMMARY OF THE STATUS OF
RESEARCH ON THE MECHANISM
OF COMBUSTION

Prepared by
Arthur D. Little, Inc.

CLEARINGHOUSE
FOR FEDERAL SCIENTIFIC AND
TECHNICAL INFORMATION

Hardcopy Microfiche

\$6.60 \$.75 65 pp. 00

ARCHIVE COPY



3 D C
JUL 11 1966

Bumblebee Series

October 1946

Report No. 47

Copy No. 207

DISTRIBUTION OF THIS
DOCUMENT IS UNLIMITED

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
8621 Georgia Avenue
Silver Spring, Maryland

Operating Under Contract NOrd 7386
With the Bureau of Ordnance, U. S. Navy

A SUMMARY OF THE STATUS OF RESEARCH
ON THE MECHANISM OF COMBUSTION

prepared by

Arthur D. Little, Incorporated

X

1		
---	--	--

This report is one part of a SURVEY OF THE LITERATURE ON COMBUSTION prepared by Arthur D. Little, Inc., for the Applied Physics Laboratory, The Johns Hopkins University. The Survey was conducted and the report written under the direction of Dr. W. H. Avery.

October 1946

DISTRIBUTION OF THIS
DOCUMENT IS UNLIMITED

N O T E

Attach this statement to
BUMBLEBEE Report No. 47 by
pasting this page to the blank
page opposite the Table of Con-
tents.

FOREWORD

Nature and Scope of
"SURVEY OF THE LITERATURE ON COMBUSTION"
as prepared by Arthur D. Little, Incorporated,
for the Applied Physics Laboratory,
The Johns Hopkins University.

I. Description of Project

A. Task Statement - "to provide a survey of information available on chemical reactions which may be of interest for rocket and ram-jet propulsion systems; information is particularly desired on studies leading to the elucidation of mechanisms of gas-phase oxidation reactions, including investigations of the initiation of reaction, explosion limits, flame propagation and stability, nature of reaction intermediates, and of accelerating and inhibiting agents."

B. Problem Statements

1. Experimental Methods - "to consist in the preparation of a report dealing with experimental methods which have been developed for the elucidation of reaction mechanisms; report should include a description of each method, nature of the information obtained, critical evaluation, references and suggested methods of applying new experimental techniques."
2. Reaction Studies - "to consist in the preparation of a card index giving,
 - a. Chemical oxidation reactions on which significant data are available for the problems outlined in the task statement; each reference should include conditions of pressure, temperature and flow, nature of measurements, and summary of results.
 - b. Short abstracts of the more significant papers in the field covered by the task statement.
 - c. Short abstracts of all publications dealing with reactions which have been applied in the propulsion of rockets and ram-jets."

3. Summary of Status - "to consist in preparation of a report which summarizes briefly the material examined under Problem 2 above, showing the state of present knowledge with regard to the various aspects of the study of gas-phase oxidation reactions."

II. Scope and Preparation Procedure

A. Classified Material - the successful accomplishment of the task as outlined above required a review of both unclassified and classified information because most of the work on combustion carried out during the war - both here and abroad - was of a classified nature. Unfortunately no complete index of such material had been made nor had all of the pertinent classified reports, which numbered several thousand, been collected in a single agency. Consequently, with minor exceptions, within the time and funds at the task's disposal it was possible only to determine the sources of classified material and to indicate what general information was available from each. A description of these sources and a resume of the information obtained has been submitted as a separate part of the report to APL/JHU. Index cards were prepared for the few pertinent classified references which were disclosed in the investigation of these sources; in addition index cards and abstracts were prepared of the classified reports pertinent to this task which are located in the files of the Chemical Engineering Department of Massachusetts Institute of Technology. One copy of the classified abstracts and a set of all classified index cards are located at APL/JHU.

B. Unclassified Material - Review of unclassified material was carried out as follows:

1. Index cards carrying short abstracts were prepared for all references (approximately 3000) listed in CHEMICAL ABSTRACTS under the headings given below for the period beginning with 1936 (Volume 30) and running through August 1 1946. (Earlier work was not abstracted because of the existence of excellent summaries of combustion research, prior to 1936, by Jost, von Elbe & Lewis, and others). Subject headings abstracted were:

Calorific Value	Heat of Combustion	Oxygen
Combustibility	Hydrocarbon Oils	Ozone
Combustibles	Hydrocarbons	Paramagnetism
Combustion	Igniters	Photochemistry
Decomposition	Ignition	Projectiles
Detonation	Inflammability	Promoters
Explosibility	Inhibitors	Reaction Kinetics
Explosions	Isotopes	Reactions

Explosives	Jet Propulsion	Rockets
Flames	Mass Spectrograph	Sound
Flash Point	Mirrors	Spectroscopy
Free Radicals	Molecular Beams	Thermal conductivity
(Detection of)	Ortho & para hydrogen	Thermodynamic properties
Fuels	Oxidation	Thermodynamics
Heat of Activation		Turbines

2. On the basis of the short abstracts on the index cards, the references were divided in terms of relative importance into A, B, C and D groups. Articles rated A were judged to be of first importance to the general understanding of the mechanism and phenomena of combustion. Those grouped under B were judged to be either of less general excellence or more limited pertinence; C references were thought to have significance such that they would be worthy of consideration only in a thorough study of some phase of combustion research; the D group comprised references believed to be relevant only to special or derivative phases of combustion research.
3. After the references had been grouped as indicated above, abstracts of the A and B items as given in CHEMICAL ABSTRACTS were reviewed. If the importance of any given article seemed to warrant a more complete treatment than appeared in this publication, the Zentralblatt reference was consulted. If neither appeared adequate the original article was studied and a more thorough review prepared.
4. Typed copies were prepared of all A and B abstracts plus those from CHEMICAL ABSTRACTS of the C articles which were not reviewed before being copied. Although these abstracts numbering some 2,000 were not requested in the task statement, it was felt that they would add greatly to the value of the survey. They, along with the card index are on file at APL/JHU.
5. With the A and B references as a basis, supplemented by the reading of selected references in whole or in part, the summary reports requested in Problems 1 and 3 were prepared.

III. Distribution of Results of the Survey

- A. Problem 1 - Summary report has been issued by APL/JHU as Section T Memorandum CM-366, dated October 1946.
- B. Problem 2 - The card index and abstracts described above are located at APL/JHU where they can be consulted by anyone visiting the laboratory.
- C. Problem 3 - Summary report is presented herewith as BUMBLE-BEE Report No. 47, dated October 1946.

TABLE OF CONTENTS

	<u>Page No.</u>
A. Introduction	1
B. Fundamental Considerations	1
C. The Hydrogen-Oxygen Reaction	5
(1) Mechanism and Kinetic Theory	
(2) Induction Period	
(3) Thermal Reaction	
(4) Lower Limit of Ignition or Explosion	
(5) Second Explosion Limit	
(6) Reaction in the Region of the Third Explosion Limit	
(7) Effect of Additives.	
(8) Measurement or Calculation of Concentration or Reaction Rates of Intermediates.	
(9) Photochemical and Spectroscopic Observations.	
(10) General	
D. Combustion of Carbon Monoxide	10
(1) Slow Thermal Reaction	
(2) Reaction in the Region of the Upper Explosion Limit	
(3) Spectroscopic and Photochemical Studies	
(4) Mixtures and Additives.	
E. Oxidation of Hydrocarbons	12
(1) Methane	
(a) Ignition and Induction Period	
(b) Second Pressure Limits	
(c) Reactions of Intermediates and Products.	
(d) Photochemical and Spectroscopic Studies.	
(e) Studies of Additives and Mixtures	
1. Ethylene	
2. Nitrogen	
3. Methyl Nitrite	
4. Surface	
(f) Studies of Reaction Mechanism or Kinetics.	
(g) Thermal Decomposition of Methane.	

	<u>Page No.</u>
(2) Ethane	16
(a) Reaction Kinetics	
(b) Photochemical Studies	
(c) Thermal Decomposition	
(3) Propane	17
(a) Inflammation Ranges	
(b) Reaction Kinetics and Physical Measurements.	
(c) Studies of Mixtures and Additives	
(d) Mechanism	
(4) Butane	19
(a) Ignition	
(b) Studies of Mixtures and Additives	
(c) Mechanism	
(d) Thermal Decomposition	
(5) Pentane	20
(a) Ignition	
(b) Reaction Kinetics	
(c) Studies of Mixtures and Additives	
(d) Mechanism	
(e) Thermal Decomposition	
(6) Ethylene	21
(a) Ignition	
(b) Reaction Kinetics	
(c) Studies of Mixtures and Additives	
(7) Acetylene	21
(a) Reaction Kinetics	
(c) Spectroscopic Studies	
(d) Thermal Reaction	
(8) Aromatics	22
(a) Ignition	
(b) Reaction Kinetics	
(c) Thermal Decomposition	
(9) Studies of Miscellaneous Hydrocarbons	23
(a) Ignition and Induction Phenomena	
(b) Reaction Kinetics	
(c) Mechanism	
(d) Studies of Mixtures and Additives	
(e) Spectroscopic Studies	
(f) Thermal Decomposition	

F. Oxidation of Aldehydes	24
(1) Formaldehyde	
(a) Mechanism and Kinetics	
(b) Thermal Decomposition	
(c) Photochemistry	

	<u>Page No.</u>
(2) Acetaldehyde	25
(a) Ignition and Induction Period	
(b) Mechanism and Experimental Kinetics	
(c) Studies of Mixtures and Additives	
(d) Thermal Decomposition	
(e) Photolysis	
(3) Propaldehyde	26
(a) Thermal Decomposition	
(b) Photolysis	
(4) Butaldehyde and Higher Aldehydes	27
G. Oxidation of Ketones	27
(1) Photo-oxidation	
(2) Thermal Decomposition	
(3) Photolysis	
H. Combustion of Formic Acid	27
I. Oxidation of Ethers	28
(1) Methyl Ether	
(a) Thermal Decomposition	
(2) Diethyl Ether	
(a) Spectroscopic Observations	
(b) Thermal Decomposition	
(c) Electrolytic Decomposition	
(3) Diisopropyl Ether	
(4) Dioxane	
J. Oxidation of Alcohols	29
K. Peroxide Formation and Decomposition	29
(1) Studies and Theories of Peroxide Formation	
(2) Peroxide Decomposition	
L. Oxidation and Decomposition of Miscellaneous Compounds	30
(a) Ammonia	
(b) Butyl Amine	
(c) Carbon Disulfide	
(d) Chlorine - Hydrogen	
(e) Chlorine Monoxide Decomposition	
(f) Diacetyl Reactions	
(g) Diethyl Acetal (Inflammation)	
(h) Ethylene Oxide	
(i) Hydrazine	
(j) Methyl Amine	

- (k) Methyl Iodide
- (l) Methyl Isocyanate
- (m) Nitrogen Oxides
- (n) Nitrates and Nitrites
- (o) Nitrosyl Chloride
- (p) Silanes
- (q) Sulfur Compounds
- (r) Sodium and Organic Halides

M. Theory of Chemical Kinetics	32
N. Studies of Physical Aspects of Combustion	33
(1) Studies of Physical Aspects of Ignition	
(2) Flame Propagation	
(3) Detonation	
(4) Theory and Properties of Burner Flames.	
(5) Diffusion Effects in Shock Waves	
(6) Turbulence and Mixing	
(7) Latent Energy in Flames.	
(8) Flame Temperature Measurements	
(a) Discussions of Errors and Reviews	
(b) Flame temperatures from the Emission Spectrum	
(c) Measurement by Thermometry	
(d) Temperatures by the Na-line Reversal Method	
(e) Two Color Pyrometry	
(f) By pressure rise in closed bomb.	
O. Thermodynamic Studies	35
(1) Experimental Measurements	
(2) Calculation of Thermodynamic Quantities	
P. Rocket Propulsion Chemicals	36

A SUMMARY OF THE STATUS OF RESEARCH

ON THE

MECHANISM OF COMBUSTION

A. Introduction.

In the preparation of this summary approximately 3000 papers, reports, and patents have been reviewed. Of these, roughly 800 were found to be of sufficient importance to merit further consideration. Unfortunately, because of time limitations, it has not been possible to read all of the pertinent papers. However, abstracts of these papers have been read and those papers, which from their abstracts seemed to be of primary importance, have been used as a basis for the preparation of this summary. Since the primary emphasis of this review has been placed on mechanism of reaction, detailed discussion of empirical phenomena is omitted. An attempt is made, however, to indicate sources of material, to aid the reader, interested in any special topic, to find the published reports on that topic. All compounds listed in Chemical Abstracts as promoters or inhibitors of reaction have been incorporated in the card index supplied with the report. No further explicit reference is made to them in this summary.

B. Fundamental Considerations.

Through the work of a large number of investigators, among whom Nernst, Bodenstein, Bonhoeffer, Polanyi, Rice, Eyring and Semenov may be mentioned particularly, the fundamental principles underlying the phenomena of gaseous oxidation reactions are rather well understood. Very briefly the salient features of the theory may be summarized as follows:

Reaction between two molecular species, such as H_2 and O_2 , proceeds through a series of bimolecular or, occasionally, termolecular collisions of molecules or atoms until final products are formed which are stable under the given experimental conditions. Usually reaction between two molecules or atoms does not take place unless the particles possess energy considerably in excess of the mean equilibrium thermal energy for the given temperature, i.e., an activation energy is required for reaction to take place. This is true even though energy is liberated in the reaction, i.e., internal energy is converted to translational, rotational, vibrational, electronic energy or radiation.*

In addition to fulfilling the energy requirement, the colliding molecules must also be properly oriented if they are to react. Thus,

* Although accurate values of the activation energy cannot usually be calculated, it is possible from thermodynamics to set lower limits to these values. Thus, the activation energy for an endothermic elementary reaction cannot be significantly less than the energy absorbed in the process.

the expression for the reaction rate includes a factor giving the collision probability of the two species which may be interpreted as representing the probability that the two colliding particles will possess sufficient energy to react, and finally, a steric factor representing the probability that the orientation requirements will be fulfilled. The first term will depend on the concentrations of the reacting particles, on their dimensions and on the forces of attraction or repulsion which act between them. The general expression for the rate will have, then, the following form:

$$\text{Rate} = Z s f(T) g([\text{reactants}])$$

in which Z is the number of collisions in unit volume, in unit time,
 s is the steric factor,
 f(T) is an undetermined function of the temperature,
 g([\text{reactants}]) is an undetermined function of the concentration of reactants, products and additives.

For a particular system reacting at constant temperature,

$$\text{Rate} = K g([\text{reactants}]).$$

The constant K is called the rate constant of the reaction.

To an approximation sufficiently close for most purposes, the product (at constant pressure) of Z and s may be considered proportional to the square root of the temperature and equated to $AT^{1/2}$ where A is a constant, and f(T) may be replaced by $e^{-E/RT}$, in which E is the activation energy (equal to the difference between the energy required for reaction of the given particles, and their average thermal energy, and R is the gas constant. With these substitutions,

$$K = AT^{1/2} e^{-E/RT}.$$

An understanding of the mechanism of a reaction, for our purposes, will be taken to mean the ability to estimate quantitatively the effects on the reaction of changes in temperature, concentration of reactants, nature and dimensions of the reaction chamber, and presence of additives. Both the rate of the reaction and the nature and amounts of products formed may be affected by these changes.

Investigations of a wide variety of chemical reactions have shown that only in rare instances can the mechanism of a reaction be understood without the postulation of one or more intermediate steps between the initial reaction and the formation of final products. This follows from the fact that the lowest energy process that can occur during the collision of two molecules is ordinarily one that involves the breaking of only a single bond. Thus reaction between molecules is most likely to occur by separate steps, involving first, dissociation of the least tightly bound molecule, followed by reaction of atoms or radicals so formed with other molecules. The

radicals or atoms produced in this step react further, the process finally being stopped by the reactants being consumed or the intermediates being neutralized by chain breaking reactions in the gas phase or adsorption on the container walls.

One of the simplest examples of reactions of this type is that between H_2 and bromine. The reaction involves the following steps:¹

- (1) $Br_2 \longrightarrow 2 Br - 45.2 \text{ Kcal}$
- (2) $Br + H \rightleftharpoons HBr + H - 16.4 \text{ Kcal}$
- (3) $H + Br_2 \rightleftharpoons HBr + Br - 40.5 \text{ Kcal}$
- (4) $Br + Br + M \rightleftharpoons Br_2 + M + 45.2 \text{ Kcal}$

Inspection of the above scheme shows that steps (2) and (3) constitute a cycle or chain in which the active hydrogen and bromine atoms are regenerated, while two molecules of HBr are formed. Thus, if other considerations did not prevent it, all of the H_2 and Br_2 could react by the continued repetition of steps (2) and (3) once reaction (1) had furnished an initial bromine atom.

Two factors prevent ramification of the chains in this reaction. First, reaction (2) requires an activation energy of something over 16 Kcal so that only unusually energetic bromine atoms or hydrogen molecules can react and, secondly, bromine atoms are removed by reaction (4). The chain length is determined then by the relative probability of reactions (2) and (4).

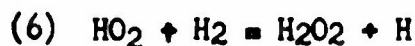
The probability of reaction (4) is decreased by the fact that atoms can recombine only if a third body is present to carry off the energy released in the reaction. Polyatomic radicals may in some cases be able to recombine in the absence of a third body, since the possibility exists of distribution of the energy among several types of vibration and stabilization of the molecule for the period between collisions.

The hydrogen bromine reaction introduces several concepts of value in understanding the mechanism of gaseous oxidations:

- (1) The importance of intermediates in bimolecular reactions.
- (2) The influence of the energy requirements of the individual processes on the reaction kinetics.
- (3) The possibility of chain formation.
- (4) The termolecular character of most recombination or association reactions.

- (5) The possibility of the course of the reaction's being affected by the reaction chamber's dimensions, because of chain breaking or initiation at the surface of the vessel.

Two further concepts are required for the elucidation of gaseous oxidation reactions: That of chain branching and that of formation of degenerate branching chains. Chain branching, originally postulated by Semenov², may be illustrated by the following sequence of reactions, which form part of the mechanism for the hydrogen oxygen reaction proposed by Von Elbe and Lewis^{3a}.



.....



Consideration of the above scheme shows that each hydrogen atom reacting according to (3) leads to two particles capable of carrying on chains. A similar situation holds for reaction (4). As a consequence, if conditions are provided whereby reactions (5) and (12) become relatively unimportant, the number of chains will increase at a rate comparable to the collision number and explosion may result. Reactions in which chain branching may occur may be expected, therefore, to show great sensitivity to experimental conditions, since the effect of the branching is to raise to a high power ($\sim 10^9$) any slight change in the relative probabilities of the chain branching and chain ending processes. [(2)and(3) vs. (5)and(12)]

"Degenerate branching" of chains was postulated by Semenov^{3b,3c,3d} to explain certain phenomena observed in the oxidation of hydrocarbons, such as the induction period and "cool flame". The phenomenon may be illustrated by the following hypothetical series of steps.

- (1) $RH \longrightarrow R + H$
- (1) $RH + H \longrightarrow R + H_2$
- (2) $R \longrightarrow R' + \text{olefin}$
- (3) $\text{olefin} + O_2 \longrightarrow \text{peroxide}$
- (4) $\text{peroxide} \longrightarrow \text{aldehydes}$
- (5) $\text{aldehydes} \longrightarrow \text{free radicals} + CO + H$
- (6) $R' + RH \longrightarrow R'H + R$

This (purely illustrative) chain is propagated by reactions (1), (2) and (6). Branching can occur by (3), (4) and (5). However, since the products formed in (3) and (4) are relatively stable, the branching reactions are insignificant until an appreciable concentration of these intermediates is built up. Reaction may then proceed with rapidity or even violence.

The above review indicates that even a qualitative understanding of the mechanism of a reaction requires a knowledge of the identity, relative concentrations and method of reaction or destruction of the intermediate particles. Quantitative understanding requires, in addition, an estimation of the rate constants and activation energies of the individual step reactions, and the accommodation coefficients, collision cross-sections, diffusion rates, radiation probabilities and the rates of interchange of translational, rotational, vibrational and electronic energies among species and degrees of freedom.

In the following pages a brief attempt is made to show what progress toward these objectives has been made in the study of the oxidation of hydrogen, CO, methane and other hydrocarbons. Other oxidation processes are then reviewed and finally reference is made to papers dealing with the theory of chemical kinetics, with various physical aspects of combustion, with thermodynamic studies of fuels or combustion, and with rocket propellants.

C. The Hydrogen-Oxygen Reaction.

In common with other oxidation reactions, in which chain branching occurs, the hydrogen-oxygen reaction shows sharply defined regions of temperature and pressure in which the reaction rate increases rapidly with time so that explosion may result. Within these regions, as explained above, the probability of chain branching is greater than that of chain breaking. The boundaries of the regions are characterized by

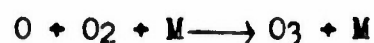
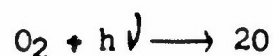
the manner in which they are observed experimentally, as the low pressure limit, the second limit and the high pressure or thermal limit. Thus, if a mixture of given composition is introduced into a vessel at a temperature of 575° C. and the pressure gradually increased, reaction will be negligible until the pressure reaches about 5 mm., when an explosion will occur. Mixtures introduced at pressures in the range 5 to about 150 mm. will explode in approaching thermal and kinetic equilibrium. Above this pressure, reaction proceeds at a finite but constant rate until a pressure of about 350 mm. is reached, when a third explosion occurs.

The effects on the hydrogen-oxygen reaction of pressure, temperature and vessel dimensions are well explained by the most recent mechanism proposed by Von Elbe and Lewis^{3a}.

- (1) $\text{H}_2\text{O}_2 + \text{M} = 2 \text{OH}$
- (2) $\text{OH} + \text{H}_2 = \text{H}_2\text{O} + \text{H}$
- (3) $\text{H} + \text{O}_2 = \text{OH} + \text{O}$
- (4) $\text{O} + \text{H}_2 = \text{OH} + \text{H}$
- (5) $\text{H} + \text{O}_2 + \text{M} = \text{HO}_2 + \text{M}$
- (6) $\text{HO}_2 + \text{H}_2 = \text{H}_2\text{O}_2 + \text{H}$
- (7) $2\text{HO}_2 \xrightarrow{\text{surface}} \text{H}_2\text{O}_2 + \text{O}$
- (8) $\text{H} + \text{O}_2 + \text{H}_2\text{O}_2 = \text{H}_2\text{O} + \text{O}_2 + \text{OH}$
- (9) $\text{HO}_2 + \text{H}_2\text{O}_2 = \text{H}_2\text{O} + \text{O}_2 + \text{OH}$
- (10) $\text{H}_2\text{O}_2 \xrightarrow{\text{surface}} \text{H}_2\text{O} + 1/2 \text{O}_2$
- (11) $\text{H}_2 + \text{O}_2 \xrightarrow{\text{surface}} \text{H}_2\text{O}_2$
- (12) $\text{H}, \text{O}, \text{OH} \xrightarrow{\text{surface}} \text{destruction}$

In a very detailed examination of the kinetic consequences of this scheme, Von Elbe and Lewis show that it is in quantitative agreement with the observed low and high pressure explosion limits and third explosion limit, and that it correctly predicts the effect of change in vessel dimensions. The authors give values of the rate constants and activation energies of all reactions except (2) and (4). Concentrations of HO_2 and H are also presented.

The scheme has been substantiated by work of Nalbandjan^{4a,b,c}, who derives a theoretical expression for the dependence of the induction period on pressure and temperature, from which the activation energy of reaction (3) is deduced to be 23 K calories. (Instead of the value of 17 Kcal quoted by Von Elbe and Lewis). Zel'dovich and Semenov, however, from a study of the combustion of moist CO arrived at a value of 18 Kcal for the same reaction. The Von Elbe and Lewis scheme is also in agreement with results of photo chemical experiments by Smith⁵ who postulated reactions (2), (3), (4), (5), (6), and (7) plus



to explain his data.

Oldenberg and Morris⁶ state in a preliminary report that the Von Elbe and Lewis theory does not correctly predict their observations on the effect of Pyrex vessel size on the third explosion limit although it is strikingly successful in predicting the effect of added gases on the second explosion limit. Undoubtedly further inconsistencies in the quantitative aspects of the theory will appear as further experimental work is performed, but it seems unlikely that major changes in the basic mechanism will be required.

Studies of various phases of the hydrogen-oxygen reaction by a number of investigators are listed below under appropriate headings.

(1) Mechanism and Kinetic Theory.

An early treatment upon which most of the later work is based was given by Kassel⁷. Polyakov and co-workers⁸⁻¹⁶ have discussed the mechanism with particular reference to the prediction of H_2O_2 formation. Frank-Kamenetskii¹⁷ has applied his theory of thermal explosions with success to the third explosion limit. Behrens¹⁸ and Clusius and Gutschmidt¹⁹ have discussed the effect of hydrogen diffusion on the rate of flame propagation. The latter authors experimented with light and heavy hydrogen.

(2) Induction Period.

In addition to the work of Nalbandjan previously mentioned, Shtern, Kravets and Sokolik²⁰ have studied the auto-ignition of mixtures of hydrogen and air.

(3) Thermal Reaction.

The thermal reaction has been the subject of a number of studies by Oldenberg and co-workers²¹⁻²⁴, by Chirkov²⁵, who concludes from his work that the mechanism of the reaction is different at high and low pressures, and by Neimark, Kulashina and Polyakov²⁶.

(4) Lower Limit of Ignition or Explosion.

The effect of various experimental conditions, including the presence of metal wires of different compositions, was investigated by Kimata, Aomi and Goto²⁷ and Horiba and Goto²⁸. Data on the lower region of ignition in quartz and pyrex vessels with and without added argon were obtained by Biron and Nalbandjan²⁹. Tanzin³⁰ and Garner and Pugh³¹ have studied the propagation of low pressure flames in tubes. Hayakawa and Goto³² have studied the spark ignition of $H_2 - O_2$ mixtures at low pressures.

(5) Second Explosion Limit.

An extensive investigation of the explosion limit as a function of pressure was made by Dykman³³ using various types of sparks for ignition. Von Elbe and Lewis³⁴ have discussed the consequences for the theoretical mechanism of the effect of water vapor on the second explosion limit. Much of the work mentioned under Section (4) is also pertinent to this topic.

(6) Reaction in the Region of the Third Explosion Limit.

The theory and kinetics of the third explosion limit have been studied by Von Elbe³⁵, Heiple and Lewis³⁶, Oldenberg and Sommers³⁷, Oldenberg³⁸ and Ziskin³⁹.

(7) Effect of additives.

References are listed without discussion under appropriate headings.

- (a) Nitrogen Dioxide.
Von Elbe and Lewis^{40,41}, Norrish and Dainton^{42, 5},
Crist and Wertz⁴³.
- (b) Nitrosyl Chloride.
Dainton and Norrish^{44,45}.
- (c) Nitrous Oxide
Danby⁴⁶.

- (d) Inert Gases
Von Elbe and Lewis⁴⁷, Jorriksen⁴⁸, Valkenburg⁴⁹
- (e) Hydrogen Peroxide
Dainton and Norrish⁵⁰
- (f) Silver
Nalbandjan^{51,52}
- (g) Carbon Monoxide
Prettre⁵³

(8) Measurement or Calculation of Concentration or Reaction Rates of Intermediates.

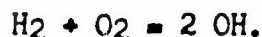
Studies of the concentration of hydroxyl radicals in reacting hydrogen-oxygen mixtures have been made by Avramenko^{54,55}, by Kondrat'ev and Ziskin⁵⁶ and by Oldenberg and co-workers^{57,58,59,60}. Kondrat'ev⁶¹ has reviewed spectroscopic data on OH obtained from various sources. Rodeoush⁶² has studied products obtained from reactions in a glow discharge and mentions the use of the luminescence of the reaction $\text{NO} + \text{O}$ as a test for the presence of oxygen atoms. Von Elbe and Lewis⁶³ discuss reactions of HO_2 and give rate constants for the reactions



and



Semenov⁶⁴ gives rate constants for the latter reaction and



Baker⁶⁵, Kondrat'eva and Kondrat'ev⁶⁶, and Mackenzie and Mowbray⁶⁷ discuss the decomposition of hydrogen peroxide.

(9) Photochemical and Spectroscopic Observations.

In addition to the work of Smith⁵, the photochemical oxidation of hydrogen has been studied by Nalbandjan⁶⁸ and Pavlyuchenko⁶⁹. Kitagawa⁷⁰ has found spectroscopically, water molecules with vibrational energies as high as 50 Kcal. A chain mechanism is proposed in explanation. Kondrat'ev^{70a} has computed the temperature dependence of the lower limit from spectroscopic measurements of hydroxyl concentration. Oldenberg^{70c} has studied OH radicals produced by a discharge in water vapor.

(10) General

A clear and interesting review of the mechanism of the hydrogen-oxygen reaction has been given by Von Elbe^{70b} who lists the following values for some of the rate constants for the reaction steps.

Absolute Values of Rate Coefficients and Activation Energies

$$k_3 = 1 \times 10^{-17} \sqrt{T/803} e^{-(1-T/803)17000/803R} \text{ cm.}^3 \text{ sec.}^{-1}$$

$$k_6 = 4.23 \times 10^{-19} \sqrt{T/803} e^{-(1-T/803)24000/803R} \text{ cm.}^3 \text{ sec.}^{-1}$$

$$k_9 = 2.0 \times 10^{-16} \sqrt{T/803} e^{-(1-T/803)14000/803R} \text{ cm.}^3 \text{ sec.}^{-1}$$

$$k_{1,H_2} = 3.39 \times 10^{-22} \sqrt{T/803} e^{-(1-T/803)45500/803R} \text{ cm.}^3 \text{ sec.}^{-1}$$

$$k_{5,H_2} = 3.7 \times 10^{-35} \sqrt{T/803} \text{ cm.}^6 \text{ sec.}^{-1}$$

$$k_{H_2O_2 + H + O_2 \rightarrow H_2O + O_2 + OH} = 6.8 \times 10^{-35} \sqrt{T/803} \text{ cm.}^6 \text{ sec.}^{-1}$$

$$k_{7,H_2} = 17.2 \times 10^{20} \sqrt{T/803} \text{ cm.}^{-1} \text{ sec.}^{-1}$$

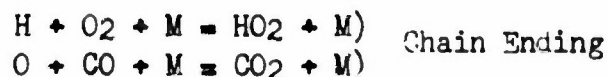
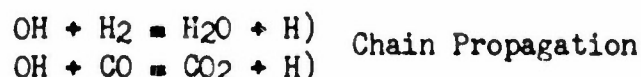
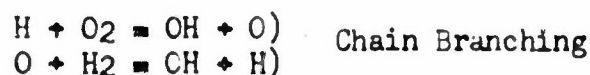
D. Combustion of Carbon Monoxide.

Although the reaction of carbon monoxide and oxygen appears superficially to present less complicating features than that of hydrogen and oxygen, the details of the mechanism are less well understood. Experimentally, the reaction shows a low pressure and high pressure explosion limits occurring at 600°C at about 13 and 30 mm. respectively (Zyono⁷¹). There is some doubt, however, that explosion can occur in the absence of sources of hydrogen atoms. Buckler and Norrish⁷², Lewis and Von Elbe⁷³ have proposed a reaction mechanism involving CO₃, ozone and oxygen atoms which satisfactorily explains the upper explosion limit as a function of pressure and added gases. This mechanism has been criticized by Jost⁷⁴ who feels the evidence favors a branching due to energy chains rather than radicals. Work of Gaydon⁹¹ on the absorption of hot oxygen in dry CO-O₂ flames is of interest in this connection. Zatsiorskii, Kondrateev and Solnishkova^{87b} have studied spectroscopically the reaction between CO and O₃, which is of importance in the mechanisms proposed by Von Elbe and Lewis³ and Jost⁷⁴.

Interpretation of the reaction is rendered difficult by its extreme

sensitivity to traces of hydrogen or other impurities, and most of the work since 1938 has been concentrated on mixtures of carbon monoxide and oxygen containing additives.

Buckler and Norrish^{75,76} appear to have established the following mechanism for the hydrogen sensitized reaction:



Support for the mechanism was found in experiments on the ignition limits using D₂ instead of H₂ and using inert gases. The work of Norrish is in agreement with experiments of Kondrat'eva and Kondrat'ev⁷⁷ who have measured the concentration of hydroxyl radicals present during the reaction. Their measurements show that the hydroxyl concentration is one hundred times the equilibrium thermal concentration and prove that the radical is produced by chemical means. Comparison of the rate of disappearance of OH with the rate of formation of CO₂ shows that the two rates are in agreement, substantiating the hypothesis that CO₂ is formed primarily by



with an activation energy of 10 Kcal. From a study of the emission of radiation of moist and dry carbon monoxide flames, Kondrat'eva and Kondrat'ev⁷⁸ concluded that the reaction mechanism was different in the two mixtures. Their measurements of the total amount of radiation⁷⁹ indicated that one molecule in ten of CO₂ was in an excited state. Kondrat'ev⁸⁰ and Zel'dovich and Semenov^{81a,81b} have reviewed experimental work.

Additional work on carbon monoxide oxidation is summarized below under appropriate headings.

(1) Slow Thermal Reaction.

Korneieva⁸² has studied the effect of platinum wires of various lengths on the rate of the slow oxidation. The results are interpreted to indicate a predominantly homogeneous chain reaction at temperatures above 600°C but with some evidence of catalysis or inhibition by surface effects. Below 600°C, the reaction becomes more heterogeneous.

(2) Reaction in the Region of the Upper Explosion Limit.

The effect of quartz surface on the reaction has been studied by Kondo and Toyama⁸³.

(3) Spectroscopic and Photochemical Studies.

Kondrat'eva and Kondrat'ev⁸⁴ have determined the chain length in the photo-oxidation of CO as a function of the temperature. The length varies from 2 at 400°C to 560 at 490°C where the dark reaction is appreciable. Faltings, Groth and Hardeck⁸⁸ and Groth^{88a} have studied the photochemical decomposition at room temperature using CO and CO, H₂ mixtures. In the latter case, HCO was postulated as an intermediate product to explain H₂CO production. Flame studies have been made by Kondrat'eva and Kondrat'ev^{77,78,79,80,84,85,86,87,87b} Tawde⁸⁹, Bonhoeffer⁹⁰, Gaydon^{91,92,93,94,95,96}, who finds evidence in the last reference for a high concentration of atomic oxygen in both dry and moist CO flames, and Jorissen⁹⁷.

(4) Mixtures and Additives.

Further studies have been conducted by Walls⁹⁸, who found evidence for a change in mechanism with change in pressure in H₂, CO oxidations; Karzhavina⁹⁹ who studied the effect of water at temperatures over 1000°C; by Dijkman¹⁰⁰ who studied CH₄-CO-O₂ mixtures; by Drozdov and Zel'dovich¹⁰¹ who investigated the effect CCl₄ on the flame propagation; and Calhoun¹⁰², Brown and Crist¹⁰³ who studied CO-NO₂-O₂ mixtures.

E. Oxidation of Hydrocarbons.

Because of the large number of intermediate reactions possible in the oxidation of hydrocarbons, only a few general conclusions have been drawn regarding the reaction mechanisms. The oxidation of all hydrocarbons displays certain general features indicating that the reactions proceed through the formation of degenerate chains, but the specific intermediates involved have not been established. It is evident that much more extensive studies, possibly supplemented by new techniques, are required of the oxidation of the specific hydrocarbons before an approach can be made to a quantitative understanding of the processes involved.

(1) Methane.

Studies of the partial oxidation of methane by a number of investigators, e.g. Garner and Ham,¹⁰⁴ Slotin and Style¹⁰⁵, Bone and Gardner¹⁰⁶, and Degens¹⁰⁷ have shown that formaldehyde

methyl alcohol, formic acid and traces of peroxides are formed, as well as water, carbon monoxide, hydrogen and carbon dioxide. The reaction shows an induction period which varies with pressure and temperature in accordance with the degenerate chain theory of Semenov (Gardner and Ham¹⁰⁴). Addition of any of the intermediates shortens the induction period, indicating that they or products of their decomposition play a part in the chain reaction. Formally, these observations may be explained by a number of theories, of which, superficially at least, the most satisfactory is that of Von Elbe^{70b}. The following scheme is proposed:

- (1) $\text{OH} + \text{CH}_4 \longrightarrow \text{H}_2\text{O} + \text{CH}_3$
- (2) $\text{CH}_3 + \text{O}_2 \longrightarrow \text{CH}_3\text{O}_2 \longrightarrow \text{H}_2\text{CO} + \text{OH}$
- (3) $\text{OH} + \text{H}_2\text{CO} \longrightarrow \text{H}_2\text{O} + \text{HCO}$
- (4) $\text{HCO} + \text{O}_2 \longrightarrow \text{HO}_2 + \text{CO}$
- (5) $\text{HO}_2 + \text{H}_2\text{CO} \longrightarrow \text{HCOOH} + \text{OH}$
- (6) $\text{HCOOH} \longrightarrow \text{H}_2\text{O} + \text{CO}$

Evidence for all of the above reactions appears to be on rather firm ground through work of Von Elbe and Lewis¹⁰⁸, Van Tiggelen^{136b}, and Harteck, Groth and Faltings⁸⁸ among others. The mechanism explains the induction period and, qualitatively the explosion limits, but additional steps would be required to explain the remaining intermediate products. A more extensive discussion of these points is given in references 70b, 74, 109, 110 and 141.

Additional work pertinent to the oxidation of methane is reviewed below.

(a) Ignition and Induction Period.

Kane¹¹¹ has compared ignition temperature as a function of pressure for a number of the simpler aliphatic hydrocarbons, alcohols and aldehydes. The purpose was to determine the relative reactivity of alcohols, aldehydes and parent hydrocarbons. For the single C-atom set, the order aldehyde > alcohol > hydrocarbon was observed. Townend¹¹² has tabulated

ignition temperatures and inflammability limits of a wide variety of hydrocarbons. Sachsse¹¹³ has measured induction times and ignition temperatures in methane oxygen mixtures by a flow method. Polyakov and Kuleshina¹¹⁴ have studied the effect of mixture ratio and added gas. Malinovskii and Malyar¹¹⁵ and Davies¹¹⁶ have studied the ignition of methane by hot wires.

(b) Second Pressure Limits.

Explosion pressure as a function of mixture composition was studied by Dijkman and Brandhof¹¹⁷.

(c) Reactions of Intermediates and Products.

Kushnerev and Shekter¹¹⁸ obtained about 50% H₂CO by reaction of methane with oxygen atoms. Soloveichik¹¹⁹ found that ozone gave only partial oxidation of methane. Staronka and Czerski^{120,121} studied the variation in the amounts of methyl alcohol and formaldehyde formed as a function of time and mixture ratio. Polyakov and Stadnik¹²² found that an organic peroxide is not a primary oxidation product.

(d) Photochemical and Spectroscopic Studies.

Groth and Laudenklos¹²³ and Groth¹²⁴ studied the photodecomposition of methane. An extensive study of flames of hydrocarbons including methane has been made by Vaidya.¹²⁵ Bands of OH, HCO, C₂, CH have been identified. The bearing of the observations on the mechanism of combustion is discussed. Similar studies have been made by Guenault,¹²⁶ Coppens,¹²⁷ and Bell.¹²⁸

(e) Studies of Additives and Mixtures.

1. Ethylene

Rivin¹²⁹ found that purified methane air mixtures did not detonate. On addition of .3% ethylene, the mixture could be exploded.

2. Nitrogen

Polyakov and co-workers^{130, 130a} have studied the formation of nitrogen oxides as a function of composition pressure and dimensions of the reaction vessel.

3. Methyl Nitrite

Gimmelman and Neiman¹³¹ found that methyl nitrite eliminated the induction period in methane and ethane combustions.

4. Surface

Norrish and Reagh¹³² have examined theoretically and experimentally the influence of surface on the reaction and the bearing of the results on the chain theory. Polyakov and co-workers^{133,134} investigated the effect of platinum on the induction period. Jorissen and Lebbink¹³⁵ found that the reaction temperature of methane-oxygen mixtures varied between 170°C and 540°C depending on the salt used to coat the inside of the reaction vessel. LiF gave the lowest temperature, RbI the highest, while in the uncoated vessel, the minimum temperature for observable reaction was 250°C.

(f) Studies of Reaction Mechanism or Kinetics.

Van Tiggelen^{136a,b} has proposed a mechanism for methane oxidation depending on hydroxyl radicals and HCO radicals for chain propagation. This is essentially the same process as proposed by Von Elbe. Prettre¹³⁷ proposes that two mechanisms operate in the oxidation of methane and ethane, one involving peroxidation at temperatures around 200 to 300°C and the other above 500°C, where peroxides apparently play no part. Polyakov and Korneeva¹³⁸ have investigated the kinetics of slow combustion of methane at low pressures in the presence of platinum surfaces. Norrish¹³⁹ has studied in considerable detail the kinetics of methane combustion. Among other things, his work shows that chlorine at low pressures inhibits reactions, but at high pressures catalyses it; iodine has a marked anti-catalytic effect in the neighborhood of ignition temperature. Addition of small amounts of formaldehyde removes the induction period but does not alter the maximum velocity of the reaction. Nitrogen peroxide has a strong sensitizing reaction and HCl catalyses the production of formaldehyde. The mechanism proposed involves an atom chain modified to include the phenomena of degenerate branching. Semenov^{139a} has also proposed an atom chain to explain oxidation of methane and other hydrides. Newitt and Gardner^{139b} have investigated the compounds formed during the induction period in the slow oxidation of methane. Ogura¹⁴¹ has reviewed the oxidation of methane.

(g) Thermal Decomposition of Methane.

Patat^{140,140a} has studied the reaction $\text{CH}_3 + \text{H}_2$ by means of para hydrogen. Hinshelwood and co-workers^{142,143} used nitric oxide to study the chain length in the methane decomposition, and Letort and Duval¹⁴⁴ found evidence with tellurium mirrors that CH_2 radicals are formed in an electric discharge through methane.

(2) Ethane.

No examinations of ethane oxidation of sufficient generality to serve as a basis for a complete mechanism have been proposed. However, various aspects of the oxidation have been studied and these are summarized under the appropriate headings.

(a) Reaction Kinetics.

Sadovnikov¹⁴⁶ has studied ethane oxidation at pressures of 50 to 200 mm., temperatures in the range of 600 to 750°C with various reaction vessels and found that the kinetics can be explained in terms of the Semenov theory of branching chain reactions. Andreev¹⁴⁷ has investigated the influence of water, carbon dioxide and carbon monoxide on the kinetics. Gimmel'man, Neiman, and Sokov¹⁴⁸ have investigated the effect of nitrogen dioxide and methyl nitrite on the region of inflammation of ethane-oxygen mixtures. Fernandez¹⁴⁹ has investigated the effect of ozone on the combustion of a number of hydrocarbons including ethane. Chirkov¹⁵⁰ studied the action of water vapor on the kinetics of ethane oxidation.

(b) Photochemical Studies.

The photochemical decomposition of ethane has been studied by Faltings¹⁵¹, who found the primary products to be methyl radicals.

(c) Thermal Decomposition.

Thermal decomposition of ethane has been investigated by Hobbs and Hinshelwood¹⁵², Theile^{153,154}, Storch and Kassel¹⁵⁵, Steacie¹⁵⁶, Steacie and Shan¹⁵⁷, Kuchler and Theile¹⁵⁸, and Dintses¹⁵⁹. Rice and Herzfeld¹⁶⁰ have examined the bearing of new values of the heats of activation on the mechanism of the thermal decomposition of ethane, which they proposed earlier.

(3) Propane.

A tentative scheme for the oxidation of propane, proposed by Von Elbe^{70b}, is presented on the following page. An enormous amount of research would be required to prove or disprove its validity. In the main, the mechanism predicts correctly the products obtained by Newitt and co-workers^{161,162} who have made careful studies of the intermediates formed by slow oxidation. These workers found n propyl, isopropyl, ethyl and methyl alcohols, formaldehyde and higher aldehydes, acetone and traces of peroxides in the product of the slow oxidation at pressures above ten atmospheres. Harris and Egerton^{162a} found propylene and H_2O_2 also. Other investigations of propane are summarized below under appropriate headings.

(a) Inflammation Ranges.

The cool flame range of propane in air at ordinary temperatures and pressures above 12 atm. has been determined by Hsieh and Townend¹⁶³. Van der Hoeven¹⁶⁴ has studied the low pressure limit.

(b) Reaction Kinetics and Physical Measurements.

The kinetics of propane oxidation have been studied by Pease^{165,166,166a} and by Newitt and Thorne¹⁶⁷. Van der Poll and Westerdijk¹⁶⁸ have measured the flame temperature of propane oxygen mixtures and Ribaud and Gaudry¹⁶⁹ have investigated the effect of pressure on the velocity of flame propagation.

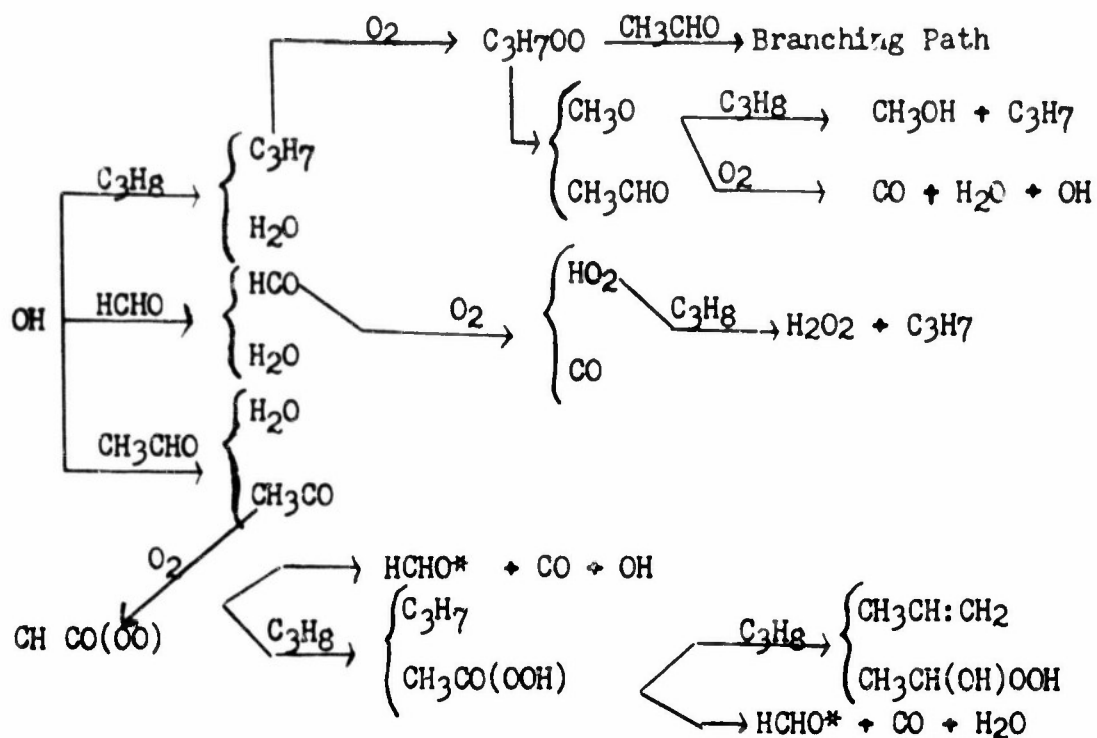
(c) Studies of Mixtures and Additives.

Fernandez¹⁴⁹ found that ozone accelerates propane oxidation, Kane¹⁷⁰ has studied the effect of nitrogen peroxide on the ignition of propane butane and acetaldehyde. His results suggest a different mechanism of oxidation at high and low temperatures depending on the stability of the intermediate hydrocarbons. From studies of the effect of surface treatment on the ignition characteristics, Day¹⁷¹ concluded that peroxides were not of primary importance in the phenomena of cool flames.

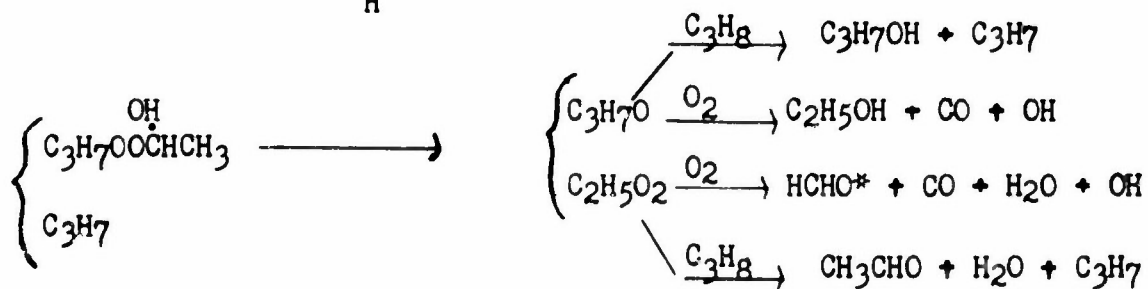
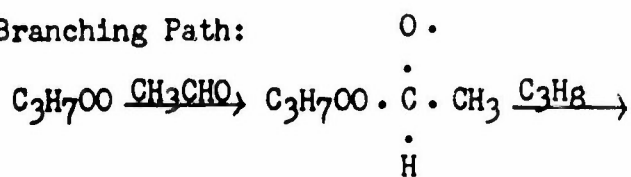
(d) Mechanism.

A mechanism of propane oxidation involving propane molecules was proposed by Pease¹⁷² in 1935.

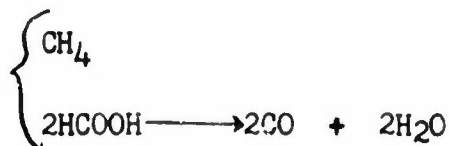
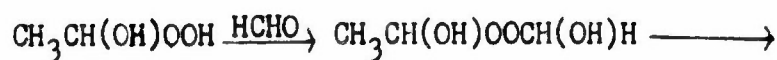
Tentative Scheme of Chain Reaction Between Propane and Oxygen



Branching Path:



Side Reactions:



* Pease and Munro report that a test for this aldehyde was negative.
J. Am. Chem. Soc., 56, 2034 (1934)

(e) Thermal Decomposition.

Burk¹⁷³ has proposed a theory for the decomposition of straight chain hydrocarbons which he feels is superior to that of Rice. He assumes that every C-C bond is equivalent and that reaction occurs when a given amount of energy is accumulated in a single bond. The rate is given then by the probability of the localization of the requisite energy.

(4) Butane.

The mechanism of the oxidation of butane and the higher straight chain paraffins is presumably similar to that of propane. No general discussion will be attempted of the mechanism of these reactions.

(a) Ignition.

Andreev¹⁷⁴ has investigated the effect of pressure and temperature on the "cold" and "hot" flames of butane. Neiman and Tutakin^{175,176} studied the kinetics of the cold flame phenomena and concluded that the results were evidence for the chain theory of reaction. Pushlenkov¹⁷⁷ showed that the silent discharge reduces the induction period of the cold flame.

(b) Studies of Mixtures and Additives.

Aivazov, Neiman and Khanova¹⁷⁸, Avramenko and Neiman¹⁷⁹, and Aivazov and Neumann^{179a} studied the effect of H₂, CO₂, diethyl and diisopropyl ethers, acetone, NO₂ and acetaldehyde on the induction period of the cold and hot flames. Only diethyl ether, aldehyde and NO₂ promote ignition. Blat, Gerber and Neiman^{180,181} studied the effect of diethyl peroxide and methyl hydroperoxide on the induction period and derived an expression, based on the Semenov theory, which gave quantitative agreement with their results. Smittenberg and Kooijman^{181a} have studied the effect of lead tetraethyl on the flame velocity and concluded that the antiknock action of the lead was caused by its effect on the preflame reaction rather than on the flame speed. The effect of ozone has been investigated by Fernandez¹⁴⁹ and the effect of NO₂ by Kane¹⁷⁰. Schuit^{181b} has made an extensive study of the effect of surface and of a large number of additives.

(c) Mechanism.

The role of peroxides in the formation of cold and hot hydrocarbon flames has been reviewed by Neiman¹⁸².

(d) Thermal Decomposition.

The thermal decomposition of butane has been studied by Echols and Pease^{183,184}. The decomposition induced by free radicals is discussed by Rice and Polly¹⁸⁵ and Steacie and Folkins¹⁸⁶, the NO inhibited reaction by Steacie¹⁸⁷. An alternative to Rice's theory has been proposed by Burk¹⁷³.

(5) Pentane.

(a) Ignition.

The ignition delay and slow oxidation of pentane oxygen mixtures have been shown by Prettre^{188,189} and Shtern, Kravets and Sokolik¹⁹⁰ to be in accord with predictions of the Semenov theory.

(b) Reaction Kinetics.

Further kinetic studies have been made by Aivazov and Neiman¹⁹¹ and Prettre¹⁹².

(c) Studies of Mixtures and Additives.

Aivazov and Neiman^{179a,193} observed the effect of addition of N_2 , NO_2 and CH_3CHO on the induction period of cold flames. Belov^{193a} investigated the effect of diisopropyl ether and proposed an integral equation valuable in predicting the length of the induction period. Prettre¹⁹⁴ has studied the inhibition action of hydrogen and of the metal walls¹⁹⁵. Fernandez¹⁴⁹ has studied the action of ozone in the slow combustion and Kanel¹⁷⁰, the effect of NO_2 . Neiman¹⁸² reviews the role of peroxides in the formation of hydrocarbon flames.

(d) Mechanism.

Aivazov and Neiman¹⁹⁶ propose a two stage mechanism to explain the low temperature combustion of pentane.

(e) Thermal Decomposition.

Gray and Travers¹⁹⁷ have studied neopentane decomposition. Mechanisms of hydrocarbon decomposition have been proposed by Rice and Polly¹⁸⁵ and Burk¹⁷³.

(6) Ethylene.

Apparently the mechanism of ethylene oxidation resembles that of the saturated hydrocarbons, the principal difference in the products being the appearance of ethylene oxide. Jost¹⁹⁸ has found evidence from the spectrum that the reaction involves hydroxyl radicals, as reactions of saturated hydrocarbons appear to. Smith^{198a} has also studied the flame spectrum.

(a) Ignition.

Forsyth and Townend¹⁹⁹ and Kane²⁰⁰ have determined the inflammation range of ethylene at various pressures and found that NO₂ facilitates combustion.

(b) Reaction Kinetics.

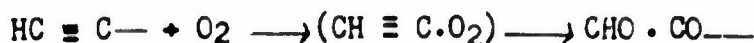
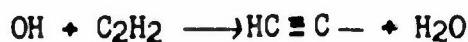
The slow oxidation of ethylene in the presence of varying lengths of platinum wire has been studied by Polyakov and Vainshtein²⁰¹ and Polyakov²⁰². Burning velocities and inflammability ranges were investigated by Young and Krase²⁰³.

(c) Studies of Mixtures and Additives.

Bone²⁰⁴ has studied the effect of dilution with inert gases on explosions of ethylene and oxygen.

(7) Acetylene.

The oxidation of acetylene probably proceeds through the initial formation of an acetyl radical, which reacts with oxygen to form a glyoxal radical (Lewis and Von Elbe^{70b}):



(a) Reaction Kinetics.

Steacie²⁰⁵ investigated the oxidation of acetylene and proposed a mechanism involving direct oxidation as the first step. Bone²⁰⁴ studied the effect of inert gases on the explosive combustion. Khitrin^{205a} studied the effect of pressure on the rate of flame propagation.

(b) Spectroscopic Studies.

Avramenko^{206,206a} measured the OH concentration and found that the number of OH radicals was proportional to the combustion rate. Jorrisen⁹⁷ studied the behavior of flames burning in a combustible atmosphere. Rossikhin and Timkovskii^{207,208} studied the effect of a high frequency discharge on the flame spectrum. No significant effect was found. Geib and Vaidya^{208a} studied the flame in atomic oxygen and Tominaga and Okamoto^{208b} the flame in Cl₂ and Br₂.

(c) Thermal Reaction.

Frank-Kamenetskii²⁰⁹ investigated the kinetics of the polymerization reaction.

(8) Aromatics.

An extensive series of investigations of the oxidation of aromatics has been conducted by Burgoyne and Newitt²¹⁰⁻²¹⁴ and Fahlbusch^{214a}. The reactions are characterized by primary oxidation of the side chains followed by phenol formation and then ring rupture. A detailed mechanism has not been proposed. Vaidya^{214b} concludes from spectroscopic studies that oxygen is first incorporated in the ring.

(a) Ignition.

Maccormac and Townend²¹⁵ studied the spontaneous ignition under pressure. Liviu²¹⁶ investigated the ignition potentials of the xylenes.

(b) Reaction Kinetics.

The kinetics of the slow combustion of benzene have been studied by Amiel²¹⁷. The products contained phenol and benzoquinone but no peroxides. Fahlbusch^{214a} has reviewed (1942) the oxidation, thermal and photochemical decomposition of simple aromatic compounds.

(c) Thermal Decomposition

Hein and Vesee²¹⁸ studied free radical formation from

pyrolysis of benzene and toluene at 900 - 1100°C. Unequivocal evidence for the tolyl radical was found but the product from benzene could not be identified.

(9) Studies of Miscellaneous Hydrocarbons.

(a) Ignition and Induction Phenomena.

Damkohler and Eggersgluss²¹⁹ investigated the products formed by rapid compression without ignition of gasoline air mixtures. Using a similar technique Jost et al^{220,220a} obtained curves of induction period vs temperature for heptane, isooctane and benzene. Spontaneous ignition and slow combustion of paraffin and olefin hydrocarbons have been discussed by Newitt and Townend²²¹, Hsieh and Townend¹⁶³, Day and Pease^{166a}, Teichmann²²², and Townend²²³. Reutenauer²²⁴ determined the upper and lower ignition regions of ketene, decalin and dipentene. Treer²²⁵ has tabulated values of the constants in an equation useful for predicting ignition times.

(b) Reaction Kinetics.

Thermal studies of hydrocarbon oxidation have been made by Estradere²²⁶. Kroger and Kaller²²⁷ studied the concentration of peroxides in cetane oxidized for varying time intervals. Maillard and Friedrich²²⁸ determined the products of incomplete combustion of light hydrocarbons. The preliminary reactions in a gasoline engine were studied by Peletier, van Hoogstraten, Smittenberg and Kooyman²²⁹, and the oxidation of cracked gases by Pigulevskii and Gulyaeva²³⁰.

(c) Mechanism.

Gervart and Frank-Kamenetskii²³¹ have discussed the periodic character of the cold flame of hydrocarbon-air mixtures under turbulent flow, in terms of the Frank-Kamenetskii theory. George, Rideal and Robertson²³² found support for the primary formation of hydroperoxides in oxidation through experiments on catalyzed and uncatalyzed oxidation of alkyl benzenes and long chain aliphatic hydrocarbons. Jost, Muffling and Rohrmann²³³ proposed (1936) a generalized chain reaction for hydrocarbon oxidation. Prettre²³⁴ discusses the negative temperature coefficient of hydrocarbon oxidation in terms of the formation of an intermediate which may decompose

to give branching or stable products. Semenov²³⁵ gives a preliminary theory to explain hydrocarbon oxidation. Townend²³⁶ discusses the possible connection between "blue flames" and peroxide decomposition. Ubbelohde^{237,238} has reviewed the oxidation of paraffins. Von Elbe²³⁹ proposed (1937) a mechanism for hydrocarbon oxidation. Von Elbe and Lewis²⁴⁰ have discussed the relation between hydrocarbon oxidizability and engine knock.

(d) Studies of Mixtures and Additives.

Briner, El-Djabri and Paillard²⁴¹ and Tawada²⁴² studied the ozonization of hexane, heptane and octanes. Maess²⁴³ studied the accelerating effect on the oxidation of heptane, of free radicals formed from azomethane decomposition. Ubbelohde²⁴⁴ discusses the effect of pro-detonant additives on hydrocarbon combustion. Vyrubov²⁴⁵ studied the effect of ozone and hydrogen on oxidation in Diesel engines.

(e) Spectroscopic Studies.

Kondrat'ev and Ziskin²⁴⁶ showed that the hydroxyl radical concentration in hydrocarbon flames is several hundred times the equilibrium concentration, indicating that these radicals are an important factor in hydrocarbon oxidation. Townend²⁴⁷ mentions chemiluminescence as a test for hydrogen atoms in flames. Gaydon^{247a} discusses the spectra of chilled hydrocarbon flames.

(f) Thermal Decomposition.

Küchler²⁴⁸ has found the thermal decomposition of cyclohexene to be a homogeneous first order reaction. Mayor²⁴⁹ has reviewed the free radical theory of hydrocarbon decomposition. Rice and Polly²⁵⁰ have explained the inhibiting effect of nitric oxide in terms of chain breaking. Burk¹⁷³ has proposed an alternative to the Rice theory.

F. Oxidation of Aldehydes.

Although aldehydes occur as intermediates in the oxidation of hydrocarbons and are themselves important as fuel constituents, few studies of their oxidation have been attempted. The theory of their oxidation has not progressed beyond the stage at which it was discussed by Jost.⁷⁴

(1) Formaldehyde.

(a) Mechanism and Kinetics.

Snowden and Style²⁵¹ and Spence²⁵² postulated the intermediates CH_2O_2 and CH_2O_3 to explain their observations of the kinetics of formaldehyde oxidation. Bone and Gardner¹⁰⁶ measured the oxidation rate and found no evidence of an induction period.

(b) Thermal Decomposition.

The thermal decomposition has been studied by Patat and Sachsse²⁵³ using para hydrogen as a test for free radicals. Rollefson and Faull²⁵⁴ investigated the effect of iodine.

(c) Photochemistry.

Photochemical investigations of formaldehyde decomposition have been made by Gorin²⁵⁵. The photooxidation has been studied by Carruthers and Norrish²⁵⁶ who obtained about 50% conversion of formaldehyde to formic acid.

(2) Acetaldehyde.

More extensive kinetic studies have been made of acetaldehyde than of any other oxygen containing hydrocarbon. Unfortunately, most of these studies have dealt with the photo or thermo decomposition and, consequently, give only indications of the manner in which the oxidation proceeds. There is some evidence to support the view that the reaction chain involves the two radicals: $\text{CH}_3\text{CO}\cdot$ and $\text{CH}_3\text{CO}\cdot\text{OO}\cdot$ (Bodenstein²⁵⁷). Aivazov²⁵⁸ in a careful study of the oxidation and the effect of peracetic acid on the kinetics, (peroxides were determined by analysis and polarographic means), concluded that his data were in accord with the peroxide theory of oxidation.

(a) Ignition and Induction Period.

Aivazov²⁵⁹ has studied the cold and hot flames and determined the temperature dependence of the induction periods. Baron²⁶⁰ studied the effect of pressure on ignition temperature. Keyer and Neimann²⁶¹ investigated the variation of induction period with composition.

(b) Mechanism and Experimental Kinetics.

Newitt^{262,263} in an extensive study of the oxidation determined the products formed at various degrees of reaction as well as the dependence of ignition on temperature and pressure. In the analysis two types of peroxides were distinguished.

(c) Studies of Mixtures and Additives.

Kane¹⁷⁰ showed that nitrogen peroxide catalyzed the ignition of acetaldehyde.

(d) Thermal Decomposition.

The thermal decomposition of acetaldehyde has been studied by Brenschede and Schumacher²⁶⁴, Burton^{265,266}, Fletcher²⁶⁷, Leifer and Urey²⁶⁸, who analyzed the products with a mass spectrograph, Letort^{269,270}, Patat and Sachsse²⁷¹ and Rollefson²⁵⁴.

(e) Photolysis.

Grahame²⁷², Gorin^{273,274}, Mitchell and Hinshelwood²⁷⁵, Leighton²⁷⁶, who reviews (1938) the status of the knowledge of aldehyde and ketone photolysis. Carruthers and Norrish²⁵⁶ studied the photo-oxidation and showed that peroxides and biacetyl are formed.

(3) Propaldehyde.

The only extensive investigation of propaldehyde combustion is that of Newitt^{262,263}, who showed that the boundary values for the upper slow combustion is given by the Semenov equation. Newitt and Townend²⁷⁷ have reviewed the combustion phenomena of the higher aldehydes.

(a) Thermal Decomposition.

The thermal decomposition has been studied by Patat and Sachsse²⁷¹ and Rollefson and Faull²⁵⁴.

(b) Photolysis.

May, Taylor and Burton²⁷⁸ have used the Paneth method for detection of free radicals from photolysis of propaldehyde. Mitchell and Hinshelwood²⁷⁵ have studied the NO inhibition and Leighton²⁷⁶ (1938) has reviewed the photochemical studies of aldehydes and ketones.

(4) Butaldehyde and Higher Aldehydes.

Newitt and Townend²⁷⁷ have reviewed the processes taking place during the autoignition. Briner and co-workers²⁷⁹⁻²⁸³ have investigated the oxidation of butaldehyde and benzaldehyde by mixtures of oxygen and ozone. Chain lengths and inhibitor effects have also been studied. Payne and Lemon²⁸⁴ have studied the mechanism of aldehyde oxidation by H_2O_2 . Leighton²⁸⁵ has investigated the photolysis of butaldehyde and isobutaldehyde.

G. Oxidation of Ketones.

Fahlbusch^{217a} has reviewed work prior to 1942 on the oxidation, and thermal and photo decomposition of ketones. No further work has been done on the direct oxidation.

(1) Photo-oxidation.

Rice and Schildknecht²⁸⁶ showed the products from the photo-oxidation of acetone to be principally acetic acid and formaldehyde. Small amounts of peroxides were formed. Fugassi²⁸⁷ found that the photo-oxidation of acetone produced a blue fluorescence, which changed to green when the oxygen was all consumed. This provided a test for traces of oxygen.

(2) Thermal Decomposition.

Gantz and Walters²⁸⁸, Gantz²⁸⁹, Smith and Hinshelwood²⁹⁰, Davoud and Hinshelwood²⁹¹, Steacie and Alexander²⁹² have studied the thermal decomposition of acetone under various conditions.

(3) Photolysis.

The photolysis of acetone has been investigated by Feldman, Burton, Ricci and Davis²⁹³, Gorin^{255,274}, Spence²⁹⁴ and Glazebrook and Pearson²⁹⁵. Gorin^{255,274} has studied also methyl ethyl ketone and Glazebrook and Pearson^{295,296} have determined the relative amounts of radicals formed from $MeEtCO$, $MePrCO$, $Me(iso-Pr)CO$, $MeBuCO$, Pr_2CO , $(iso-Pr)_2CO$, $(tert-Bu)_2CO$ and $(sec-Bu)_2CO$.

H. Combustion of Formic Acid.

Bone and Gardner¹⁰⁶ showed that only CO , CO_2 , H_2 and H_2O are formed in appreciable amounts from the combustion of formic acid. Patat and Sachsse²⁵³ studied the thermal decomposition in the presence of para hydrogen and concluded that no radicals were present in the decomposing gas.

I. Oxidation of Ethers.

(1) Methyl Ether.

Ermolova and Neiman²⁹⁷ have studied the reaction kinetics and induction periods for dimethyl ether and found good agreement with the predictions of the Semenov theory. Addition of diethyl peroxide decreases the induction period. Pannetier and Laffitte^{298, 299} determined the inflammability limits of mixtures of methyl ether with air and oxygen using a spark. The effects of surface and nitrogen addition were also investigated.

(a) Thermal Decomposition.

The thermal decomposition has been studied by Thompson and Meissner³⁰⁰, Stavely³⁰¹, and Leifer and Urey²⁶⁸.

(2) Diethyl Ether.

Ignition phenomena and the kinetics of propagation of cool and hot flames have been investigated by Baron²⁶⁰, Ermakova³⁰², Gibyanskii³⁰³, and Townend and co-workers³⁰⁴⁻³⁰⁶. Kane and Pandit³⁰⁷ by study of the sensitizing action of nitrogen dioxide on low temperature ignition found evidence that acetaldehyde is primarily involved in the formation of cool flames.

(a) Spectroscopic Observations.

Kondrat'ev³⁰⁸ has pointed out that bands found by Emeleus in diethyl ether flames (C.A. 27, 2381) appear in the fluorescence spectrum of formaldehyde. This is evidence that the cold flame of diethyl ether contains excited formaldehyde molecules. Hsieh and Townend³⁰⁹ have studied the green flames produced in ether oxidation and showed that they may be ascribed to C₂.

(b) Thermal Decomposition.

The thermal decomposition of diethyl ether has been studied by Patat³¹⁰, Hobbs³¹¹ and Fletcher³¹².

(c) Electrolytic Decomposition.

Pearson³¹³ has studied reactions of the radicals produced by electrolysis of ether in solution.

(3) Diisopropyl Ether.

Belov^{193a} studied the ignition phenomena of diisopropyl ether and obtained an integral equation expressing the dependence of the induction period on the pressure and temperature.

(4) Dioxane.

Küchler and Lambert³¹⁴ have studied the thermal decomposition of dioxane in the temperature range 723 - 808° K. at pressures from 30 to 80mm.

J. Oxidation of Alcohols.

The combustion of methyl alcohol has been investigated by Bone and Gardner¹⁰⁶ who showed that it was more resistant to oxidation than formaldehyde. Jorissen, Van Selms and Kreulen³¹⁵ showed that oxidation of methyl and ethyl alcohols occurs with simultaneous decomposition. Geib³¹⁶ studied the flame of CH_3OD and showed that OD bands were not emitted.

K. Peroxide Formation and Decomposition.

Evidence has accumulated during the past two decades which indicates that peroxides play an important part in the oxidation of almost all organic compounds. (See, for example, Von Elbe's scheme for propane oxidation page 18). Since it is also known that stable peroxides act as prodetonants in internal combustion engines, a considerable stimulus has been given to the study of their mode of formation and decomposition and to the development of kinetic theories in which they play an important part. It is likely that the phenomena of the induction period and of cool and hot flames can be explained in terms of an initial accumulation of peroxides followed by branching chain reactions when the peroxide concentration reaches a critical value. At high temperatures, intermediate formation of peroxides may not occur.

(1) Studies and Theories of Peroxide Formation.

Bakh³¹⁷, who was the first to propose the peroxide theory of oxidation, has reviewed its status as of 1941. Medvedev^{318,319} has shown that some features of hydrocarbon oxidation can be explained in terms of the superposition of two chain reactions, one initiated by thermal activation of the hydrocarbon molecules, the second by the decomposition of the intermediate peroxides. Substantiation of the theory was found in experiments with tetralin in which the peroxide intermediates could be isolated and studied separately. Neiman¹⁸² has discussed the role of peroxides in the formation of hydrocarbon flames and Dumanov³²⁰, Oosterhoff³²¹ and Sokolik³²² have proposed explanations of the behavior of

internal combustion engines based on peroxide formation in the compressed fuel air mixture.

(2) Peroxide Decomposition.

Harris and Egerton³²³⁻³²⁷ have studied the decomposition of ethyl hydroperoxide, propyl hydroperoxide and diethyl peroxide. Neiman and Tutakin³²⁸ have investigated the kinetics of diethyl peroxide decomposition; Ivanov, Savinova and Mikhailova³²⁹ investigated the decomposition of tetralin, its hydroperoxide, the hydroxymethyl derivative and hydroxymethyl derivative of tetrahydronaphthyl peroxide. Walker and Wild³³⁰ studied the thermal and photochemical decomposition of acetyl peroxide.

L. Oxidation and Decomposition of Miscellaneous Compounds.

The work in this section is too special and heterogeneous to make a detailed summary worthwhile. Pertinent references are therefore listed without comment.

(a) Ammonia.

Bodenstein³³¹, Tokarev and Nekrasov³³², Verbrugh³³³, Atroschenko and Sedasheva³³⁴, and Frejacques³³⁵.

(b) Butyl Amine.

Beachell and Taylor³³⁶.

(c) Carbon Disulfide and Carbonyl Sulfide.

Griffith and Hill³³⁷, Kondrat'ev and co-workers³³⁸⁻³⁴², (extensive spectroscopic studies of intermediates in CS₂ flames), Nalbandjan³⁴³, Pavlov^{344,345}, Semenov and Voronkov^{346,347}.

(d) Chlorine - Hydrogen.

Bodenstein³⁴⁸ and Bodenstein and Launer³⁴⁹.

(e) Chlorine Monoxide Decomposition.

Bodenstein and Szabo³⁵⁰.

(f) Diacetyl Reactions.

Rice and Walters³⁵¹.

- (g) Diethyl Acetal (Inflammation)
Dugleux and Laffitte³⁵².
- (h) Ethylene Oxide (Free Radicals from)
Fletcher and Rollefson³⁵³.
- (i) Hydrazine
Bamford³⁵⁴, Bamford and Bamford³⁵⁵.
- (j) Methyl Amine.
Travers and Hawkes³⁵⁶, Emeleus and Jolley³⁵⁷.
- (k) Methyl Iodide.
Blake and Iredale³⁵⁸, and Vaidya³⁵⁹ (both studies of flame spectra).
- (l) Methyl Isocyanate.
Bamford and Bamford³⁶⁰.
- (m) Nitrogen Oxides.
Lemon³⁶¹, Lowry³⁶², Stoddart³⁶³, Murzin³⁶⁴, Lewis and Hinshelwood³⁶⁵, Furman^{366,367}, Briner³⁶⁸.
- (n) Nitrates and Nitrites.
Appin, Todes and Khariton³⁶⁹, Carter and Travers³⁷⁰, Taylor and Vesselovsky³⁷¹, Thompson and Dainton³⁷², Steacie and Kata³⁷³, Steacie and Shaw³⁷⁴, Purkis³⁷⁵.
- (o) Nitrosyl Chloride.
Natanson³⁷⁶, Krauss and Saracini³⁷⁷.
- (p) Silanes.
Shantarovich³⁷⁸, Emeleus and Welch³⁷⁹.

(q) Sulfur Compounds.

Yakovlev and Shantarovich³⁸⁰, Schenk and Jablonowski³⁸¹, Emanuel^{382,383,384,385}, Emanuel, Pavlov, Semenov³⁸⁶, Kondrat'eva and Kondrat'ev^{387,388}, Brodovich³⁸⁹.

(r) Sodium and Organic Halides.

Allen and Bawn³⁹⁰.

M. Theory of Chemical Kinetics.

In this section a short survey is made of the more important developments in the kinetic theory of the processes occurring in chemical transformations.

Akulov³⁹¹⁻³⁹⁴ has extended the theory of branching chains and studied the application of the theory to the determination of induction periods, etc. He has also developed equations relating the effect of a negative catalyst (e.g. surface) to the volume of the reaction space. Dijkman^{395,396} has investigated the explosion limits for spark ignition of mixtures which pass continuously into the limits for high temperature inflammation. Evans³⁹⁷ derives Kassel's formula for the rate of an unimolecular reaction from transition state theory. Von Elbe³⁹⁸ derives an expression for the steady state rate of a chain reaction in which there are varying efficiencies of chain breaking at the walls. Frank-Kamenetskii³⁹⁹⁻⁴⁰⁵ has published several important papers on the theory of thermal reactions and has discussed the mechanism of two-stage inflammation and periodic processes in oxidation reactions. Gurney⁴⁰⁶ derives a theory for reaction chains where intermediate particles react with members of preliminary and following steps. Geib⁴⁰⁷ has studied the relation of molecular structure to reaction mechanism. Hulburt⁴⁰⁸ derives equations for reaction rates in reacting flowing systems. Jost⁴⁰⁹ and Landau⁴¹⁰ discuss the theory of thermal explosions. Meixner⁴¹¹ has discussed the "thermodynamics" of irreversible processes. Prettre⁴¹² discusses wall effects in chain reactions. O. K. Rice⁴¹³ has applied the Frank-Kamenetskii theory to explosions of azomethane, ethyl azide and methyl nitrate. The evaluation of specific rate constants in chain reactions is the subject of a review article by Rollefson⁴¹⁴. Szczeniowski⁴¹⁵ has derived a generalized combustion equation taking into account dissociation at high temperatures. Stupochenko⁴¹⁶ discusses the possibility of accumulation of molecules of a certain type around an active center and its effect on the kinetics of reaction. Semenov⁴¹⁷⁻⁴¹⁹, in an early paper (1936) gives a review of his theory. Two later papers discuss methods of determining concentration of intermediates and the effects of diffusion of chain centers to the vessel wall. Todes and co-workers⁴²⁰⁻⁴²⁴ have presented several papers on the theory of thermal explosions.

The theory and mechanism of combustion in internal combustion engines has been the subject of articles by Blume⁴²⁵, Broersma⁴²⁶, Boyd^{427,428}, Boerlage and Broeze^{429,430}, Dreyhaupt⁴³¹, Evans⁴³², Isogai⁴³³, Jost⁴³⁴, Jost and Muffling⁴³⁵, Kling⁴³⁶, Kneule⁴³⁷, Meurer⁴³⁸, Mock⁴³⁹, Newitt⁴⁴⁰, E. Schmidt and Muhlner⁴⁴¹, F.A.F. Schmidt^{442,443}, Serruys^{444,445}, Zeise^{446,447} and Zinner⁴⁴⁸.

Studies of various experimental aspects of internal combustion have been made by Ernst⁴⁴⁹, Funck⁴⁵⁰, Herele⁴⁵¹, Laure⁴⁵², Lichtenberger and Seeber⁴⁵³, Lonn⁴⁵⁴, Rassweiler, Withrow and Cornelius⁴⁵⁵, Rothrock, Spencer and Miller,⁴⁵⁶ Scheuermeyer and Steigerwald⁴⁵⁷, Shoemaker and Gadebusch⁴⁵⁸, Sokolik and Yantovskii⁴⁵⁹, Spencer⁴⁶⁰, Starkman⁴⁶¹, Wolfer⁴⁶², Watts and Lloyd-Evans⁴⁶³ and Widmaier⁴⁶⁴.

The role of free radicals in chemical reactions has been examined by Aten⁴⁶⁵, Groth⁴⁶⁶, Mandala⁴⁶⁷, Pearson and Purcell⁴⁶⁸, Rice and Teller⁴⁶⁹, Rice, Walters and Ruoff⁴⁷⁰, Staveley and Hinshelwood⁴⁷¹, Smith⁴⁷², Ubbelohde⁴⁷³ and Waters⁴⁷⁴.

General reviews of combustion kinetics and phenomena have been published by Eucken⁴⁷⁵, Flock^{476,477}, Jost⁴⁷⁸, Lewis⁴⁷⁹, Prettre⁴⁸⁰, Stevels^{481,482}, Steacie⁴⁸³, Sokolik⁴⁸⁴, Sachsse⁴⁸⁵, Thiemann⁴⁸⁶ and Wittig⁴⁸⁷. Berger⁴⁸⁸ lists data on physical properties and oxidation phenomena for over 400 compounds. Vaidya⁴⁸⁹ has reviewed the evidence for various intermediates which has been obtained from spectroscopic studies of the processes in internal combustion engines. Kondrat'ev^{490,491} and Czerlinsky and Seibt⁴⁹² have published similar reviews.

N. Studies of Physical Aspects of Combustion.

A large number of investigations have been made of phenomena, such as detonation rates, which are intimately related to combustion mechanism, but for which the physical and thermodynamic properties or state of the reactants are of more direct importance than the detailed chemical mechanism in their quantitative treatment. References to these reports are listed below under appropriate headings.

(1) Studies of Physical Aspects of Ignition.

Guest⁴⁹³, Landau⁴⁹⁴, Linnett, Raynor and Frost⁴⁹⁵, Jorissen et al⁴⁹⁶, Mole⁴⁹⁷, Paterson^{498,499}, Schade⁵⁰⁰, Semenov⁵⁰¹, Silver⁵⁰², Vaillard^{503,504}, Zel'dovich⁵⁰⁵.

(2) Flame Propagation.

Coward and Payman⁵⁰⁶, Coward, Hartwell and Georgeson⁵⁰⁷, Dient

and Shchelkin⁵⁰⁸, Denues⁵⁰⁹, Damkohler^{510,554}, Plock and co-workers^{511,512,513}, Jost and Muffling⁵¹⁴, Khitrin⁵¹⁵, Kolesnikova⁵¹⁶, Kolodtsev⁵¹⁷, Lewis and Von Elbe^{518,519}, Mache⁵²⁰, Manson⁵²¹, Malinovskii⁵²², Smith⁵²³, Townsend and McCormac⁵²⁴, Van de Poll⁵²⁵, Zel'dovich and Semanov⁵²⁶.

(3) Detonation.

Becker⁵²⁷, Broersma⁵²⁸, Jost⁵²⁹, Jost and Muffling⁵³⁰, Laffitte⁵³¹, Manson⁵³², Pfriem⁵³³, Reingold⁵³⁴, Shtsholkin⁵³⁵, Tokarev and Nekrasov⁵³⁶, Thomas⁵³⁷, Veron^{538,539}, Zel'dovich^{540,541,542}, Zouckermann and Heyberger⁵⁴³.

(4) Theory and Properties of Burner Flames.

Behrens⁵⁴⁴, Garside, Forsyth and Townsend⁵⁴⁵, Khitrin⁵⁴⁶, Lewis and Von Elbe⁵⁴⁷, Von Elbe and Mentzer⁵⁴⁸, Vasilescu⁵⁴⁹, Wolfhard⁵⁵⁰.

(5) Diffusion Effects in Shock Waves.

Cowling⁵⁵¹.

(6) Turbulence and Mixing.

Dreyhaupt^{552,553}, Damkohler⁵⁵⁴, Shvab⁵⁵⁵, Shchelkin⁵⁵⁶.

(7) Latent Energy in Flames.

David and co-workers⁵⁵⁷⁻⁵⁷⁰, Leah⁵⁷¹, Lewis and Von Elbe⁵⁷², Zeise⁵⁷³.

(8) Flame Temperature Measurements.

(a) Discussions of Errors and Reviews.

Bosanquet⁵⁷⁴, Eggert⁵⁷⁵, Von Elbe⁵⁷⁶, Fishenden and Saunders⁵⁷⁷, Hase⁵⁷⁸, Matthews⁵⁷⁹, Weissner⁵⁸⁰, Pirani⁵⁸¹, Ribaud and co-workers^{582,583}, Richardson (1945)⁵⁸⁴, Schroder⁵⁸⁵, Swallow⁵⁸⁶ and Tewes⁵⁸⁷.

(b) Flame temperatures from the Emission Spectrum.

Brinkman⁵⁸⁸, Coheur and Coheur⁵⁸⁹, Graff⁵⁹⁰, Knauss⁵⁹¹.

(c) Measurement by Thermometry.

Kobayashi⁵⁹², Larsen et al⁵⁹³, Schack⁵⁹⁴, Severinghaus⁵⁹⁵, Swart⁵⁹⁶, Thring⁵⁹⁷, Zhukovskii⁵⁹⁸.

(d) Temperatures by the Na-line Reversal Method.

David⁵⁹⁹, Van de Poll et al⁶⁰⁰, Rosenthal⁶⁰¹,
Yosida⁶⁰².

(e) Two Color Pyrometry.

Graff⁶⁰³, Naeser⁶⁰⁴, Uyehara et al⁶⁰⁵.

(f) By pressure rise in closed bomb.

Leah^{606,607}.

O. Thermodynamic Studies.

(1) Experimental Measurements.

Mathews and Hurd⁶⁰⁸ have determined the thermodynamic properties of methane. Rossini and Knowlton^{609,610} give data on the heats of combustion of the normal alkenes-1. Wartenberg⁶¹¹ determined the equilibrium constant for acetylene-hydrogen and graphite at 1750°C. Coops et al⁶¹² have measured the heats of combustion of a number of olefinic and phenyl substituted methanes and ethanes. Jessup⁶¹³ has determined the heats of combustion of the liquid paraffin hydrocarbons from hexane to decane. Pitzer⁶¹⁴ discusses methods of calculating free energies and heat contents of gaseous hydrocarbons and gives tables of values for the paraffins through heptane and for the simpler unsaturated hydrocarbons; Zeise^{615,617} presents data on the thermodynamic functions of water, CO₂ and of some additional molecules and radicals important in combustion. Burke and Hunt⁶¹⁸ have determined the heat of combustion of acetone.

(2) Calculation of Thermodynamic Quantities.

Benedict⁶¹⁹ has derived empirical equations for the thermodynamic properties of light hydrocarbons and their mixtures. Hottel and Eberhardt⁶²⁰ show how the use of Mollier diagrams simplifies combustion calculations. Pitzer⁶²¹ gives tables useful for the calculation of thermodynamic functions of molecules having restricted internal rotations. Rossin and Fehling⁶²² discuss the use of I-T diagrams in combustion calculations. Von Stein⁶²³ discusses methods of calculating dissociation equilibria. Walker^{624,625} derives expressions for the temperature, pressure and specific volume changes of a dissociating gas. Wiebe⁶²⁶ gives Mollier diagrams calculated according to Hottel and Eberhardt for octane-air and octane-water-air mixtures. Withrow and Cornelius⁶²⁷ discuss the use of thermodynamic charts in the analysis of flame picture and

pressure data. Zeise⁶²⁸ discusses the thermodynamic calculation of combustion temperatures and reactions in gas mixtures with precise consideration of all possible cracking phenomena.

P. Rocket Propulsion Chemicals.

Only a few unclassified reports on this subject have significance. Kuhn et al⁶²⁹ summarize the chemical combinations used for jet propulsion in Germany. Monofuels included 65-85% methyl nitrate in methanol, ammonium nitrate plus ammonia, nitrous oxide plus ammonia and tetranitromethane plus 8-hydroxyquinoline in 80 to 85% H₂O₂. Bifuels were made up of an oxidizing agent and a fuel. Oxidizing agents considered were: 98 - 100% nitric acid, 98-100% nitric acid plus 5 - 10% strong sulfuric acid, liquid oxygen, 80-85% hydrogen peroxide with or without calcium permanganate, and ammonium nitrate. The fuels considered were: Methanol, ethanol, hydrazine hydrate, hydrazine hydrate plus methanol, 57% m-xylidine plus 47% triethylamine, 8-hydroxyquinoline, furfuryl alcohol, vinyl ethyl ether, gasoline, diesel oil, Optol (a hydrogenated lignite tar fraction, Ergol (a mixture of Optol, tetrahydrofurane, furfuryl alcohol and aniline). Bellinger et al⁶³⁰ report on propellant systems consisting of (1) concentrated hydrogen peroxide plus permanganate, (2) red fuming nitric acid and aniline, and (3) mononitromethane plus catalyst. Lawrence⁶³¹ has discussed engineering aspects of the operation of an ethyl alcohol - oxygen propulsion unit.

BIBLIOGRAPHY

General References

- Explosions-und Verbrennungs-vorgänge in Gasen, W. Jost, J. Springer, Berlin, 1939, Photo-Lithoprint Reproduction - Edward Brothers, Inc., 1943
- Combustion, Flames and Explosions of Gases, Lewis and von Elbe, Cambridge University Press, 1938.
- The Chemical Background for Engine Research, Burk and Grummitt, Interscience Publishers, Inc., New York, 1943. (Frontiers in Chemistry, II)
- The Science of Petroleum, Dunstan, Nash, Brooks, Tizard, Vol. IV, Section on Combustion, Oxford University Press, 1938.
- Equilibrium and Kinetics of Gas Reactions, Pease, Princeton University Press, 1942.
- Chemische Gasreaktionen, Schumacher, Steinkopff, 1938, Photo-Lithoprint Production - Edwards Brothers, Inc., Ann Arbor, Michigan, 1943.
- Atomic and Free Radical Reactions, Steacie, Reinhold Publishing Corp., New York City, 1946.
- Chemical Kinetics and Chain Reactions, Semenov, Oxford Clarendon Press, 1935
- The Aliphatic Free Radicals, F. O. Rice and K. K. Rice, Reinhold Publishing Corp., New York City, 1935.
- Photochemistry of Gases, Leighton and Noyes, Reinhold Publishing Corp. New York, 1941.
- Photochemistry and the Mechanism of Chemical Reactions., Rollefson and Burton, Prentice-Hall, Inc., New York, 1939.

Arabic Numerals Refer to the Reference Number in the Text.
 Roman Numerals and Capital Letters Refer to the Card Index
 Classification of the Reference.

- 1 XIII B Schumacher, Chemische Gasreaktionen, T. Steinkopff (1938)
- 2 III A Semenov, Z. Physik, 46, 109 (1937)
- 3a III A Von Elbe and Lewis, J. Chem. Phys. 10, 366-93 (1942)
- 3b XIII A Chemical Kinetics and Chain Reactions, Semenov, Oxford
Clarendon Press, 1935.
- 3c III A Semenov, Compt. Rend. Acad. Sci. U.R.S.S. 43, 342-8;
Doklady Akad. Nauk S.S.S.R. 43, 360-6 (1944)
- 3d III A Semenov, Bull. Acad. Sci. U.R.S.S. Classe Sci. Chim. 1945,
210-22.
- 4a III B Nalbandjan, Acta Physicochimica 19, 483-496 (1944)
- 4b III B Nalbandjan, Acta Physicochimica 19, 497-507 (1944)
- 4c III B Nalbandjan, Acta Physicochimica U.R.S.S. 20, 31-4 (1945)
- 5 III B Smith, J. Am. Soc. 62, 385-93 (1940)
- 6 IV B Oldenberg, J. Chem. Phys. 11, 247 (1943)
- 7 III B Kassel, Chem. Rev. 21, 331-45 (1937)
- 8 III B Polyakov, Compt. Rend. Acad. Sci. U.R.S.S. 4, 454-5 (1934).
- 9 III B Polyakov and El'Kenbard, Acta Physicochim. U.R.S.S. 2,
397-400 (1935)
- 10 III B Polyakov, J. Phys. Chem. (U.S.S.R.) 5, 954-7 (1934)
- 11 III B Polyakov, Stadnik, El'kenbard, J. Phys. Chem.(U.S.S.R.) 5,
966-8 (1934); Acta Physicochim. U.R.S.S. 1, 817-20 (1934).
- 12 III B Polyakov, Malkin, Aleksandrovich, J. Phys. Chem. (U.S.S.R.)
5, 958-65; Acta Physicochim. U.R.S.S. 1, 821-32 (1934)
- 13 III B Polyakov, Stadnik, Malkin, El'kenbard, Neimark, J. Phys.
Chem. (U.S.S.R.) 5, 1464-9 (1934).
- 14 III B Polyakov, Acta Physicochim. U.R.S.S. 9, 517-26 (1938).
- 15 III B Polyakov, Neimark and Maksimuk, Ber. Inst. Physik. Chem.,
Akad. Wiss. Ukr. S.S.R. 7, No. 1, 21-8 (1937)
- 16 III B Polyakov, Problemy Kinetiki i Kataliza, Sbornik Trudov
Konferentsii Posvyashchennoi Sorokatiletuyu Perekisnoi
Teorii Bakha-Englera, 4, 217-25 (1945); Khim, Referat.
Zhur. 4, No. 1, 17 (1941)
- 17 XI B Frank-Kamenetskii, Acta Physicochim U.R.S.S. 13, 730-1 (1940)
- 18 IV B Behrens, Naturwissenschaften 32, 297-9 (1944)
- 19 IV B Clusius and Gutschmidt, Z. Elektrochem. 42, 498 (1936)
- 20 V B Shtern, Kravets, Sokolik, Acta Physicochim. U.R.S.S. 8,
461-80; J. Phys. Chem. (U.S.S.R.) 11, 706-19 (1938).
- 21 III B Oldenberg, J. Chem. Physics 8, 468-76 (1940)
- 22 III A Oldenberg, Sommers, J. Chem. Physics 9, 432-8 (1941)
- 23 III A Oldenberg, Sommers, J. Chem. Phys. 9, 573-8 (1941)
- 24 IV B Oldenberg, Sommers, J. Chem. Phys. 7, 279 (1939)
- 25 III B Chirkov, Acta Physicochim. U.R.S.S. 6, 915-38 (1937)

- 26 III B Neimark, Kulashina and Polyakov, Acta Physicochim. U.R.S.S. 2, 733-40 (1938)
- 27 IV B Kimata, Aomi and Goto, Rev. Phys. Chem. Japan 15, 42053 (1941)
- 28 XI B Horiba and Goto, Proc. Imp. Acad. (Tokyo) 16, 218-22 (1940)
- 29 III B Biron, Nalbandjan, J. Phys. Chem. (U.S.S.R.) 2, 132-42 (1937)
- 30 IV B Tauzin, Ann. Phys. 6, 575-662 (1936)
- 31 III B Garner and Pugh, Chem. Zentr. 1939, I, 3308; Trans. Faraday Soc. 35, 283-95 (1939)
- 32 XI C Hayakawa, Goto, Rev. Phys. Chem. Japan 15, 117-25 (1941)
- 33 III B Dykman, Rec. Trav. Chim. 57, 1059-74 (1938)
- 34 III B Von Elbe and Lewis, J. Chem. Phys. 9, 194-5 (1941)
- 35 III A Von Elbe, J. A. C. S. 59, 656-62 (1937)
- 36 III A Heiple, Lewis, J. Chem. Phys. 9, 584-90 (1941)
- 37 III B Oldenberg, Sommers, J. Chem. Phys. 9, 114-17 (1941)
- 38 III B Oldenberg, J. Chem. Physics 10, 193 (1942)
- 39 XI B Ziskin, Compt. Rend. Acad. Sci. U.R.S.S. 34, 256-8 (1942)
- 40 III B Von Elbe, Lewis, J. Am. Chem. Soc. 59, 2022-5 (1937)
- 41 III A Von Elbe, Lewis, J. Am. Chem. Soc. 61, 1350-5 (1939)
- 42 III B Norrish, Dainton, Nature 144, 30-1 (1939)
- 43 III B Crist, Wertz, J. Chem. Phys. 7, 719-24 (1939)
- 44 III A Dainton, Norrish, Proc. Roy. Soc. (London) A177, 411-20 (1941)
- 45 III A Dainton, Norrish, Proc. Roy. Soc. (London) A177, 421-47
- 46 III B Danby, J. Chem. Soc. (London) 1940, 464-8
- 47 IV B Von Elbe, Lewis, Chem. Revs. 21, 413-20 (1937)
- 48 III C Jorissen, Chem. Weekblad 37, 686-8 (1940)
- 49 III B Valkenburg, J. J., Rec. Trav. Chim. 57, 1097-1108 (1938)
- 50 III A Dainton, Norrish, Proc. Roy. Soc. (London) A177, 393-410 (1941)
- 51 III B Nalbandjan, Acta Physicochim. U.R.S.S. 19, 295-301 (1944)
- 52 III B Nalbandjan, Compt. Rend. Acad. Sci. U.R.S.S. 32, 196-8 (1941)
- 53 III A Prettre, Compt. Rend. 207, 674-6 (1938)
- 54 III A Avramenko, Acta Physicochimica U.R.S.S. 17, 197-210 (1942)
- 55 III A Avramenko, J. Phys. Chem. (U.S.S.R.) 18, 197-206 (1944)
- 56 IX A Kondrat'ev, Ziskin, J. Phys. Chem. (U.S.S.R.) 10, 360-6 (1937)
- 57 III B Frost, Oldenberg, J. Chem. Physics 4, 781-4 (1936)
- 58 III B Oldenberg, Rieke, J. Chem. Phys. 6, 439-47 (1938)
- 59 IX A Oldenberg, Rieke, J. Chem. Phys. 7, 485-92 (1939)
- 60 IX A Oldenberg, Morris, Morrow, Schneider, Sommers, J. Chem. Phys. 14, 16-18 (1946)
- 61 IX A Kondrat'ev, Uspekhi Khim. 8, (1939), 195-240
- 62 III A Rodebush, J. Phys. Chem. 41, 283-91 (1937)
- 63 III A Von Elbe, Lewis, J. Chem. Phys. 7, 710-18 (1939)
- 64 III A Semenov, Acta Physicochim. U.R.S.S. 20, 291-302 (1945)
- 65 III A Baker, Ouellet, Can. J. Research 23B, 167-82 (1945)

- 66 III A Kondrat'eva and Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 19, 178-84 (1945)
- 67 III A Mackenzie, Mowbray, Proc. Roy. Soc. (London) A185, 207-24 (1946)
- 68 III B Nalbandjan, Acta Physicochim. U.R.S.S. 11, 454-74 (1939)
- 69 III A Pavlyuchenko, J. Phys. Chem. (U.S.S.R.) 14, 877-85 (1940)
- 70 III B Kitagawa, Proc. Imp. Acad. (Tokyo) 12, 281-4 (1936)
- 70a III A Kondrat'ev, Compt. Rend. Acad. Sci. U.R.S.S., 44, 20-25 (1944)
- 70b XI:II A Von Elbe, Kinetics of Flame and Combustion, Chapter IV - The Chemical Background for Engine Research, Interscience Publishers (1943)
- 70c IX B Oldenberg, J. Phys. Chem. 41, 293-7 (1937)
- 71 III B Zyono, Rev. Phys. Chem. Japan 15, 17-30 (1941)
- 72 V B Buckler, Norrish, Proc. Roy. Soc. (London) A167, 292-318 (1938)
- 73 III B Von Elbe, Lewis, J. Am. Chem. Soc. 59, 2025-9 (1937)
- 74 XIII A W. Jost, Explosions-und Verbrennungs-vorgänge in Gasen, J. Springer, Berlin (1939)
- 75 V B Buckler, Norrish, Proc. Roy. Soc. (London) A167, 318-42 (1938)
- 76 III A Buckler, Norrish, Proc. Roy. Soc. (London) A172, 1-28 (1939)
- 77 III A Kondrat'eva, Kondrat'ev, Acta Physicochim. U.R.S.S. 12, 1-8 (1940)
- 78 III A Kondrat'eva, Kondrat'ev, Acta Physicochim. U.R.S.S. 8, 481-90; J. Phys. Chem. (U.S.S.R.) 11, 331-7 (1938)
- 79 IV A Kondrat'eva, Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 8, 124-9 (1936)
- 80 III A Kondrat'ev, Uspekhi Khim. 10, 1-15 (1941)
- 81a III A Zel'dovich, Semenov, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 1123-36 (1940); Chem. Zentr. 1941, II 301.
- 81b III A Zel'dovich, Semenov, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 1427-40 (1940)
- 82 III B Korneieva, Acta Physicochimica 11, 427-42 (1939)
- 83 III B Kondo and Toyama, Rev. Phys. Chem. Japan 13, 166-75 (1939)
- 84 III A Kondrat'eva, Kondrat'ev, Acta Physicochim. U.R.S.S. 10, 805-12 (1939)
- 85 III B Kondrat'eva, Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 13, 169-73 (1939)
- 86 IX A Kondrat'eva, Kondrat'ev, Acta Physicochim. U.R.S.S. 6, 748-54 (1937)
- 87 IX A Kondrat'eva, Kondrat'ev, Acta Physicochim. U.R.S.S. 6, 625-36
- 87b IX A Zatsiorskii, Kondrat'ev, Solnishkova, J. Phys. Chem. (U.S.S.R.) 14, 1521-7 (1940)
- 88 IX A Faltings, Groth, Harteck, Z. Physik. Chem. B41, 15-22 (1938)
- 88a IX A Groth, Z. Physik. Chem. B37, 307-14 (1937)
- 89 IX B Tawde, Patel, Current Sci. 6, 155-6 (1937)
- 90 IX B Bonhoeffer, Z. Elektrochem. 42, 449-57 (1936)
- 91 IX B Gaydon, Proc. Roy. Soc. (London) A 176, 505-21 (1940)
- 92 IX A Gaydon, Proc. Roy. Soc. (London) A178, 61-73 (1941)
- 93 IX A Gaydon, Proc. Roy. Soc. (London) A182, 199-206 (1943)
- 94 IX A Gaydon, Proc. Roy. Soc. (London) A181, 197-209 (1942)

- 95 I B Gaydon, Penney, Nature 150, 406-7 (1942)
- 96 IX A Gaydon, Proc. Roy. Soc. (London) A183, 111-24 (1944)
- 97 IV B Jorissen, Van Selms, Rec. Trav. Chim. 61, 399-411 (1942);
Chem. Zentr. 1942, II, 1205-6
- 98 III B Walls, Trans. Faraday Soc. 32, 1495-1501 (1936)
- 99 III B Karzhavina, J. Phys. Chem. (U.S.S.R.) 19, 551-63 (1945)
- 100 XI B Dijksman, Van den Brandhof, Jr., Rec. Trav. Chim. 59, 445-53,
(1940)
- 101 IV B Drozdov, Zel'dovich, J. Phys. Chem. (U.S.S.R.) 17, 134-44
(1943)
- 102 III A Calhoun, J. Chem. Phys. 5, 301-9 (1937)
- 103 III B Brown, Crist, J. Chem. Phys. 9, 840-6 (1941)
- 104 III A Garner, Ham, Proc. Roy. Soc. (London) A170, No. 940, 80-101,
(1939)
- 105 III A Slotin, Style, Chem. Zentr. 1939, I, 4454; Trans. Faraday
Soc. 35, 420-6 (1939)
- 106 III B Bone, Gardner, Proc. Roy. Soc. A154, 297-328 (1936)
- 107 III A Degens, Rec. Trav. Chim. 58, 39-57 (1939)
- 108 III A Von Elbe, Lewis, Schr. Deut. Akad. Luftfahrtforsch. 1939, No. 9,
169-71; Chem. Zentr. 1940, I, 356.
- 109 XIII B Combustion, Flames and Explosions of Gases, Lewis and Von Elbe,
1938.
- 110 III B Von Elbe, Chem. Rev. 21, 319-28 (1937)
- 111 III B Kane, J. Chem. Soc. 1937, 436-43
- 112 III B Townend, Maccormac, J. Inst. Petroleum 25, 459-86 (1939)
- 113 III B Sachsse, Z. Physik. Chem. B33, 229-41 (1936)
- 114 V A Polyakov, Kuleshina, J. Phys. Chem. (U.S.S.R.) 15, 470-4 (1941)
- 115 V B Malinovskii, Malyar, J. Tech. Phys. (U.S.S.R.) 5, 1260-70 (1935)
- 116 V B Davies, Fuel 22, 72-6 (1943)
- 117 XI B Dijksman, Van den Brandhof, Jr., Rec. Trav. Chim. 59, 445-53
(1940)
- 118 III A Kushnerev, Shekter, Compt. Rend. Acad. Sci. U.R.S.S. 32,
560-2 (1941)
- 119 III B Soloveichik, S.I., J. Gen. Chem. (U.S.S.R.) 8, 1696-8 (1938)
- 120 III B Staronka, Czerski, Roczniki Chem. 19, 259-76 (1939)
- 121 III A Staronka, Czerski, Roczniki Chem. 19, 333-46 (1939)
- 122 III B Polyakov, Stadnik, Neimark, J. Phys. Chem. (U.S.S.R.) 8, (1936)
- 123 III A Groth, Laudenklos, Naturwissenschaften 24, 796 (1936)
- 124 III B Groth, Z. Physik, Chem. B38, 366-80 (1937)
- 125 IX A Vaidya, Proc. Roy. Soc. (London) A178, 356-69 (1941)
- 126 IX A Guenault, Safety in Mines Research Board (London), 17 Ann.
Rept. 1938, 53-4.
- 127 II A Coppens, Bull. Classe Sci., Acad. Roy. Belg. 25, 530-5 (1939)
- 128 IX B Bell, Proc. Royal Society (London) A158, 429-54 (1939)
- 129 XI A Rivin, Compt. Rend. Acad. Sci. U.R.S.S. 30, 500-1 (1941)

- 130 III B Polyakov, Genkina, Acta Physicochim. U.R.S.S. 11, 443-52 (1939)
- 130a III B Polyakov, Kostyuchenko, Nosenko, J. Phys. Chem. (U.S.S.R.) 18, 115-20 (1944)
- 131 III B Gimmelman, Neiman, J. Phys. Chem. (U.S.S.R.) 9, 716-35 (1937)
- 132 III B Norrish, Reagh, Proc. Roy. Soc. (London) A176, 429-48 (1940)
- 133 III B Polyakov, Gryanenko, Compt. Rend. Acad. Sci. U.R.S.S. (N.S.) 3, 315-17 (1936)
- 134 III B Polyakov, Gryanenko, J. Phys. Chem. (U.S.S.R.) 8, 559-75 (1936)
- 135 III B Jorissen, Lebbink, Rev. Trav. Chim. 58, 959-63 (1939)
- 136a V B Van Tiggelen, Ann. Mines Belg. 44, 91-104 (1943); Chem. Zentr. 1944, I, 82
- 136b III B Van Tiggelen, Ann. Mines Belg. 42, 773-801 (1941); Chem. Zentr. 1942, II, 980-1
- 137 III A Prettre, Acta Physicochim. U.R.S.S. 9, 581-92 (1938)
- 138 III B Polyakov, Korneeva, Acta Physicochim. U.R.S.S. 9, 186-96 (1938)
- 139 III B Norrish, Proc. Roy. Soc. (London) A157, 503-25 (1936)
- 139a III A Semenov, Problemy Kinetiki i Kataliza, Sbornik Trudov Konferentsii Posvyashchennoi Sorokaletiyu Perekisnoi Teorii Bakha-Englera 4, 46-63 (1940); Khim. Referat. Zhur. 4, No. 1, 16, (1940)
- 139b III B Newitt, Gardner, Proc. Roy. Soc. A154, 329-35 (1936)
- 140 III B Patat, A. Physik. Chem. B32, 274-93 (1936)
- 140a III B Patat, Naturwissenschaften 24, 62-3 (1936)
- 141 III B Ogura, Bull. Chem. Soc. Japan 16, 262-73 (1941)
- 142 III A Hobbs, Hinshelwood, Proc. Roy. Soc. (London) A167, 447-55 (1938)
- 143 III B Staveley, Hinshelwood, Trans. Faraday Soc. 35, 845-9 (1939)
- 144 III A Letort, Duval, Compt. Rend. 219, 452-4 (1944)
- 146 III B Sadovnikov, J. Phys. Chem. (U.S.S.R.) 9, 575-91 (1937)
- 147 III B Andreev, J. Phys. Chem. (U.S.S.R.) 10, 859-65 (1937)
- 148 III B Gimmelman, Neiman, Sokov, J. Phys. Chem. (U.S.S.R.) 8, 458-67 (1936)
- 149 III B Fernandez, Anal. Fis. Quim. (Spain) 36, 235-40 (1940)
- 150 III B Chirkov, Compt. Rend. Acad. Sci. U.R.S.S. 45, 244-7 (1944)
- 151 IX A Faltings, Ber. 72B, 1207-15 (1939)
- 152 III A Hobbs, Hinshelwood, Proc. Roy. Soc. (London) A167, 439-46 (1938)
- 153 III B Theile, Z. Physik. Chem. B44, 41-52 (1939)
- 154 III B Theile, Z. Physik. Chem. B44, 41-52 (1939)
- 155 III B Storch, Kassel, J. Am. Chem. Soc. 59, 1240-6 (1937)
- 156 III B Steacie, Can. J. Research 18B, 203-16 (1940)
- 157 III B Steacie, Shane, Can. J. Research 18B, 351-7 (1940)
- 158 III A Kuchler, Theile, Z. Physik. Chem. B42, 359-79 (1939)
- 159 III B Dintses, Uspekhi Khim. 7, 404-35 (1938)
- 160 III B Rice, Herzfeld, J. Chem. Phys. 7, 671-4 (1939)

- 161 III B Newitt, Thornes, J. Chem. Soc. 1937, 1656-65.
 162 III B Newitt, Schmidt, J. Chem. Soc. 1937, 1665-69.
 162a III B Harris, Egerton, Chem. Rev. 21, 287-97 (1937)
 163 III B Hsieh, Townend, Chem. Zentr. 1939, I, 4454; J. Chem. Soc. 1939, 341-5.
 164 IV B Van der Hoeven, Ind. Eng. Chem. 29, 445-6 (1937)
 165 III B Pease, Chem. Rev. 21, 279-86 (1937)
 166 III B Pease, J. Am. Chem. Soc. 60, 2244-6 (1938)
 166a III A Day, Pease, J. Am. Chem. Soc. 63, 912-15 (1941)
 167 III B Newitt, Thornes, J. Chem. Soc. 1937, 1669-76
 168 III A Van der Poll and Westerdijk, J. Phys. et Radium (8) 1, 359-67 (1940)
 169 IV B Ribaud, Gaudry, Congr. Chim. Ind., Compt. Rend. 18me Congr., Nancy, Sept.-Oct. 1938, 18-23.
 170 III A Kane, Proc. Roy. Soc. (London) A171, 251-69 (1939)
 171 III B Day, J. A. C. S. 62, 2234-7 (1940)
 172 III B Pease, J. A. C. S. 57, 2296-9 (1935)
 173 III B Burk, J. A. C. S. 63, 3248-50 (1941)
 174 III B Andreev, Acta Physicochim. U.R.S.S. 6, 57-64 (1936)
 175 III B Neiman, Tutakin, Compt. Rend. Acad. Sci. U.R.S.S. (N.S.), 4, 127-30 (1936)
 176 V A Neiman, Tutakin, Bull. Acad. Sci. U.R.S.S., Classe Sci. Math. Nat., Ser. Chim. 1938, 329-45; Acta Physicochim. U.R.S.S. 2, 861-84 (1938).
 177 IV C Pushlenkov, Bull. Acad. Sci. U.R.S.S., Classe Sci. Chim. 1944, 122-8
 178 III B Aivazov, Neiman, Khanova, Bull. Acad. Sci. U.R.S.S., Classe Sci. Math. Nat., Ser. Chim. 1938, 307-26; Acta Physicochim. 2, 767-94 (1938)
 179 III B Avramenko, Heiman, Acta Physicochim. U.R.S.S. 10, 601-16 (1939); J. Phys. Chem. (U.S.S.R.) 13, 356-65 (1939)
 179a V B Aivazov, Neumann, Z. Physik. Chem. B33, 349-67 (1936)
 180 III A Blat, Gerber, Neiman, Acta Physicochim. U.R.S.S. 10, 273-96 (1939)
 181 III A Blat, Gerber, Neiman, J. Gen. Chem. (U.S.S.R.) 2, 732-47 (1939)
 181a IV B Smittenberg, Kooijman, Rec. Trav. Chim. 59, 593-600 (1940)
 181b III A Schuit, Rec. Trav. Chim. 60, 29-49 (1941)
 182 III A Neiman, Uspekhi Khim. 7, 341-84 (1938)
 183 III B Echols, Pease, J. Am. Chem. Soc. 61, 208-12 (1939)
 184 III B Echols, Pease, J. Am. Chem. Soc. 61, 1024-7 (1939)
 185 III A Rice, Polly, Trans. Faraday Soc. 35, 850-4 (1939)
 186 III A Steacie, Folkins, Can. J. Research 17, B, 105-20 (1939)
 187 III B Steacie, Can. Journ. Research 18B, 1-11 (1940)
 188 III B Prettre, Ann. Combustibles Liquides 11, 669-718 (1936)
 189 III B Prettre, Ann. Combustibles Liquides 12, 411-46 (1937)
 190 V B Shtern, Kravets, Sokolik, Acta Physicochim. U.R.S.S. 2, 141-62, (1938); J. Phys. Chem. (U.S.S.R.) 12, 69-80 (1938)

- 191 III B Aivazov, Neiman, J. Phys. Chem. (U.S.S.R.) 8, 88-109 (1936)
- 192 IV B Prettre, Compt. Rend. 203, 1152-4 (1936)
- 193 III B Aivazov, Neiman, J. Phys. Chem. (U.S.S.R.) 8, 543-58 (1936)
- 193a III B Belov, Trans. Leningrad Ind. Inst. 1939, No. 3, Sect. Phys. Math. No. 1, 161-84.
- 194 VIII B Prettre, Compt. Rend. 203, 619-20 (1936)
- 195 III B Prettre, Congr. Chim. Ind., Compt. Rend. 18^{me} Congr., Nancy, Sept.-Oct., 1938, 274-82.
- 196 III B Aivazov, Neiman, Acta Physicochim. U.R.S.S. 6, 279-88 (1937)
- 197 III B Gray, Travers, Trans. Faraday, Soc. 35, 868-74, 1089 (1939)
- 198 III A Jost, Naturwissenschaften 33/34, 392 (1943)
- 198a IX B Smith, Proc. Royal Society (London) A174, 110-25 (1940)
- 199 V B Forsyth, Townend, Inst. Gas. Engrs. Commun. No. 220, 12pp; Gas World 111, 358 (1939).
- 200 III B Kane, Proc. Roy. Soc. (London) A160, 174-87 (1937)
- 201 III B Polyakov, Vainshtein, J. Phys. Chem. (U.S.S.R.) 8, 576-83 (1936)
- 202 III A Polyakov, Acta Physicochim 11, 415-26 (1939)
- 203 IV B Yound, Krase, Trans. Am. Inst. Chem. Engrs. 35, 337-58 (1939)
- 204 III B Bone, Proc. Roy. Soc. A157, 234-248 (1936)
- 205 III B Steacie, McDonald, J. Chem. Physics 4, 75-81 (1936)
- 205a IV B Khitrin, Tech. Phys. U.S.S.R. 3, 926-39 (1936)
- 206 III A Avramenko, Acta Physicochim. U.R.S.S. 18, 58-68 (1943)
- 206a IX A Avramenko, Compt. Rend. Acad. Sci. U.R.S.S. 40, 110 (1943)
- 207 IV B Rossikhin, Timkovskii, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 1446-9 (1940)
- 208 IV A Rossikhin, Timkovskii, Bull. Acad. Sci. U.R.S.S., Ser. Phys. 1941, 219-21
- 208a IX A Geib, Vaidya, Proc. Roy. Soc. (London) A178, 351-5 (1941)
- 208b IX B Tominaga, Okamoto, Bull. Chem. Soc. Japan 12, 401-4 (1937)
- 209 III B Frank-Kamenetskii, Acta Physicochimica U.R.S.S. 18, 148-56 (1943)
- 210 III B Newitt, Proc. Roy. Soc. (London) A153, 448-62 (1936)
- 210a III B Newitt, Chem. Rev. 21, 299-317 (1937)
- 211 III A Burgoyne, Proc. Roy. Soc. (London) A161, 48-67 (1937)
- 211a V A Burgoyne, Proc. Roy. Soc. (London) A171, 421-33 (1939)
- 212 V B Burgoyne, Tang, Newitt, Proc. Roy. Soc. (London) A174, 379-93, III (1940)
- 213 III B Burgoyne, Tang, Newitt, Proc. Roy. Soc. (London) A174, 379-93, IV (1940)
- 214 III A Burgoyne, Proc. Roy. Soc. (London) A175, 539-63, V, (1940)
- 214a III B Fahlbusch, Gel. u. Kohle 38, 887-901, 965-74 (1942)
- 214b IX B Vaidya, Proc. Indian Acad. Sci. 2A, 352-7 (1935)
- 215 V B Maccormac, Townend, J. Chem. Soc. 1938, 238-46
- 216 XI B Liviu, Bull. Soc. Roumaine Phys. 41, 73-7 (1941); Physik, Ber. 22, 1745 (1941)

- 217 III B Amiel, Ann. Chim. 7, 70-120 (1937)
- 218 III B Hein, Messee, Ber. 76B, 430-47 (1943)
- 219 III B Damkohler, Eggersgluss, Z. Physik. Chem. B51, 157-86 (1942)
- 220 IX A Jost, Teichmann, Naturwissenschaften 27, 318-19 (1939)
- 220a III A Jost, Rögner, Z. Elektrochemie 47, 307-9 (1941)
- 221 IV A Newitt, Townend, Congr. Chim. Ind., Compt. Rend. 18me Congr. Nancy, Sept.-Oct., 1938, 1023-40.
- 222 III A Teichmann, Z. Elektrochem. 47, 297-307 (1941)
- 223 V B Townend, Chem. Rev. 21, 259-78 (1937)
- 224 V B Reutenauer, Comptes Rendues 213, 72-4 (1941)
- 225 X C Treer, Kraftstoff 16, 139-41, 171-4 (1940); Chem. Zentr. 1940, 2, 1532
- 226 III B Estradere, Pub. Sci. Tech. Ministere Air (France) No. 101, 57pp. (1937)
- 227 III B Kroger, Kaller, Oel U. Kohle in Gemeinschaft mit Brennstoff - Chemie 39, 669-79 (1943)
- 228 III B Maillard, Friedrich, Compt. Rend. 205, 673-5 (1937)
- 229 III B Peletier, Van Hoogstraten, Smittenberg, Kooyman, Chaleur et ind. 20, 120-5 (1939)
- 230 III B Pigulevskii, Gulyaeva, Trans. Exptl. Research Lab. "Khemgas", Materials on Cracking and Chem. Treatment of Cracking Products (U.S.S.R.) 3, 153-67 (1936)
- 231 IV B Gervart, Frank-Kamenetskii, E. J. Acad. Sci. U.R.S.S., Classe Sci. Chim. 1942, 210-20.
- 232 III B George, Rideal, Robertson, Nature 149, 601-2 (1942)
- 233 III B Jost, Muffling, Rohrmann, Z. Elektrochem. 42, 488-97 (1936)
- 234 III A Prettre, Compt. Rend. 207, 576-8 (1938)
- 235 III B Semenov, Acta Physicochim. U.R.S.S. 9, 453-74 (1938)
- 236 III A Townend, J. Inst. Fuel 12, 78-86 (1938)
- 237 III A Ubbelohde, Fuel 20, 97-100 (1941)
- 238 III A Ubbelohde, Proc. Roy. Soc. (London) A152, 354-78 (1935)
- 239 III B Von Elbe, J. A. C. S. 59, 976-84 (1937)
- 240 VI B Von Elbe, Lewis, Ind. Eng. Chem. 29, 551-4 (1937)
- 241 III B Briner, El-Djabri, Paillard, Helv. Chim. Acta 21, 95-108 (1938)
- 242 III B Tawada, J. Soc. Chem. Ind. Japan 39, Suppl. Binding 304 (1936)
- 243 III B Maess, Oel Kohle Erodoel Teer 15, 299-306, 321-6 (1939)
- 244 III A Ubbelohde, Congr. Chim. Ind., Compt. Rend. 18me Congr., Nancy Sept.-Oct., 1938, 456-9.
- 245 VII B Vyrubov, Dizel'istoenie 1940, No. 7, 3-10; Khim. Referat. Zhur. 4, No. 4, 15 (1941)
- 246 III B Kondrat'ev, Ziskin, J. Phys. Chem. (U.S.S.R.) 9, 542-52 (1937)
- 247 XIII B Townend, Chemistry and Industry 1945, 346-50
- 247a IX B Gaydon, Proc. Roy. Soc. (London) A179, 439-50 (1942)
- 248 III B Kùchler, Nachr. Ges. Wiss. Göttingen, Math-Physik Klasse, Fachgruppe, III. N.F. 1, 231-40 (1938)
- 249 III A Mayor, Rev. Chim. Ind. (Paris) 49, 118-23 (1940)
Chem. Zentr. 1941, I, 2233
- 250 III B Rice, Polly, J. Chem. Phys. 6, 273-9 (1938)

- 251 III A Snowden, Style, Chem. Zentr. 1939, I, 4455; Trans. Faraday Soc. 35, 426-33 (1939)
- 252 III B Spence, J. Chem. Soc. 1936, 649-57
- 253 IX B Patat, Sachsse, Nachr. Ges. Wiss. Göttingen, Math.-physik Klasse, Fachgruppe, III. 1, 41-8 (1935)
- 254 III B Rollefson, Faull, J. Am. Chem. Soc. 59, 629-9 (1937)
- 255 III B Gorin, J. Chem. Phys. 7, 256-64 (1939)
- 256 III B Carruthers, Norrish, J. Chem. Soc. 1936, 1036-42
- 257 III A Bodenstein, Rec. Trav. Chim. 59, 480-5 (1940)
- 258 III B Aivazov, Acta Physicochim. U.R.S.S. 14, 201-22 (1941)
- 259 III B Aivazov, J. Phys. Chem. (U.S.S.R.) 11, 702-5 (1938)
- 260 V B Baron, Ann. Combustibles Liquides 13, 875-947 (1938)
- 261 III B Keyer, Neimann, Acta Physicochimica U.R.S.S. 14, 451-62 (1941)
- 262 III B Newitt, J. Chem. Soc. (1939) 1703-10
- 263 III E Newitt, J. Chem. Soc. 1939, 1711-20
- 264 III B Brenschede, Schumacher, Ber. 70B, 452-6 (1937)
- 265 III B Burton, J. Chem. Phys. 7, 1080-5 (1939); Chem. Zentr. 1001, II, 1940
- 266 III A Burton, J. Am. Chem. Soc. 62, 265-7 (1940)
- 267 III B Fletcher, J. Am. Chem. Soc. 58, 2646-7 (1936)
- 268 IX B Leifer, Urey, J. Am. Chem. Soc. 64, 994-1001 (1942)
- 269 III B Letort, J. Chim. Phys. 34, 265-320 (1937)
- 270 III B Letort, J. Chim. Phys. 428-43 (1937)
- 271 IX B Patat, Sachsse, Z. Physik. Chem. B31, 105-24 (1935)
- 272 III B Grahame, J. Chem. Phys. 8, 98-105 (1940)
- 273 III B Gorin, Acta Physicochim. U.R.S.S. 9, 681-96 (1938)
- 274 III B Gorin, Acta Physicochim. U.R.S.S. 8, 513-15 (1938)
- 275 III B Mitchell, Hinshelwood, Proc. Roy. Soc. (London) A159, 32-45 (1937)
- 276 III B Leighton, J. Phys. Chem. 42, 749-61 (1938)
- 277 III A Newitt, Townend, Chimie & Industrie 45, Supplement to No. 3, 224-52 (1941); Chem. Zentr. 1942, II, 514.
- 278 III B May, Taylor, Burton, J. Am. Chem. Soc. 63, 249-54 (1941)
- 279 III B Briner, Lardon, Helv. Chim. Acta 19, 1062-74 (1936)
- 280 VII B Briner, Atti X^o Congr. Intern. Chim. 2, 175 (1938)
- 281 VII B Briner, Papazian, Helv. Chim. Acta 23, 497-513, 808 (1940)
- 282 VII C Briner, Papazian, Helv. Chim. Acta 23, 542-8 (1940)
- 283 VII C Briner, Helv. Chim. Acta 23, 590-6 (1940)
- 284 III B Payne, Lemon, J. Am. Chem. Soc. 63, 226-8 (1941)
- 285 III B Leighton, J. A. C. S. 59, 1843-9 (1937)
- 286 III B Rice, Schildknecht, J. Am. Chem. Soc. 60, 3044-7 (1938)
- 287 III B Fugassi, J. Am. Chem. Soc. 59, 2092-3 (1937)
- 288 III B Gantz, Walters, J. Am. Chem. Soc. 62, 996-7 (1940)
- 289 III B Gantz, J. A. C. S. 63, 3412 (1941)
- 290 III B Smith, Hinshelwood, Proc. Roy. Soc. (London) A183, 33-7 (1944)

- 291 III B Davoud, Hinshelwood, Nature 144, 909-10 (1939)
- 292 III B Steacie, Alexander, Can. J. Research 15, B, 295-304 (1937)
- 293 III B Feldman, Burton, Ricci, Davis, J. Phys. Chem. 13, 440-7 (1945)
- 294 III B Spence, J. Chem. Soc. 1937, 352-61
- 295 III A Glazebrook, Pearson, J. Chem. Soc. 1937, 567-71.
- 296 III B Glazebrook, Pearson, J. Chem. Soc. 1936, 1777-9
- 297 IV B Ermolova, Neiman, Acta Physicochim. U.R.S.S. 11, 679-700 (1939)
- 298 IV B Pannetier, Laffitte, Compt. Rend. 221, 553-5 (1945)
- 299 IV B Pannetier, Laffitte, Compt. Rend. 221, 623-5 (1945)
- 300 III B Thompson, Meissner, Nature 139, 1018-19 (1937)
- 301 III B Stavely, Proc. Roy. Soc. A159, 192-205 (1937)
- 302 III B Ermakova, J. Phys. Chem. (U.S.S.R.) 14, 148-56 (1940)
- 303 III B Gibyanskii, Trans. Leningrad Ind. Inst. No. 7, Sect. Phys. Math. No. 4, 54-61 (1937)
- 304 V B Hsieh, Townend, Chem. Zentr. 1939 I, 4454; J. Chem. Soc. 1939, 337-40
- 305 IV A Maccormac, Townend, J. Chem. Soc. 1940, 143-50.
- 306 IV B Townend, Chamberlain, Proc. Roy. Soc. (London) A158, 415-29 (1937)
- 307 V B Kane, Pandit, Proc. Indian Acad. Sci. 16A, 87-94 (1942)
- 308 IX B Kondrat'ev, Acta Physicochim. U.R.S.S. 4, 556-8 (1936)
- 309 III B Hsieh, Townend, Chem. Zentr. 1939 I, 4454; J. Chem. Soc. 1939 332-7
- 310 III B Patat, A. Physik. Chem. B32, 274-93 (1936)
- 311 III B Hobbs, Proc. Roy. Soc. (London) A167, 456-63 (1938)
- 312 III A Fletcher, J. A. C. S. 58, 2129-35 (1936)
- 313 III B Pearson, Trans. Electrochemical Society 82, 297 (1942)
- 314 III A Klüchler, Lambert, J. Physik. Chem. B37, 285-306 (1937)
- 315 III B Jorissen, Van Selms, Kreulen, Rec. Trav. Chim. 61, 269-79 (1942); Chem. Zentr. 1942, I, 267-8
- 316 IX A Geib, Z. Elektrochem. 47, 275-6 (1941)
- 317 III B Bakh, Problemy Kinetiki i Kataliza, Sbornik Trudov Konferentsii Posvyashchennoi Sorokaletiyu Teorii Bakha-Englera 4, 18-28 (1940); Khim. Referat Zhur 4, No. 1, 15-16 (1941)
- 318 III B Medvedev. Chem. Zentr. 1939, II, 1031; Acta Physicochem. U.R.S.S. 9, 395-420 (1938)
- 319 III B Medvedev. Sbornik Trudov Konferentsii Posvyashchennoi Sorokaletiyu Perekisnoi Teorii Bakha-Englera 1940, 28-45; Khim. Referat. Zhur 4, No. 2, 35 (1941)
- 320 III B Dumanois, Compt. Rend. 219, 87-8 (1944)
- 321 III B Oosterhoff, Rec. Trav. Chim. 59, 811-25 (1940)
- 322 III B Sokolik, Acta Physicochim. U.R.S.S. 9, 593-620 (1938)
- 323 III B Harris, Egerton, Nature 141, 472 (1938)
- 324 III A Harris, Egerton, Nature 142, 830 (1938)
- 325 III A Harris, Egerton, Proc. Roy. Soc. (London) A168, 1-18 (1938)

- 326 IV B Harris, Proc. Roy. Soc. (London) A175, 254-61 (1940)
- 327 III A Egerton, Harris, Congr. Chim. Ind. Compt. Rend. 18me Congr. Nancy, Sept.-Oct., 1938, 1123-32.
- 328 III B Neiman, Tutakin, Compt. Rend. 205, 278-80 (1937)
- 329 III B Ivanov, Savinova, Mikhailova, Compt. Rend. Acad. Sci. (U.R.S.S.) 25, 34-9 (1939)
- 330 III B Walker, Wild, J. Chem. Soc. 1937, 1132-6.
- 331 III B Bodenstein, Z. Elektrochemie 47, 287 (1941)
- 332 III B Tokarev, Nekrasov, J. Phys. Chem. (U.S.S.R.) 8, 504-13 (1936)
- 333 XI B Verbrugh, Rec. Trav. Chim. 59, 983-1020 (1940)
- 334 III B Atroshchenko, Sedasheva, J. Applied Chem. (U.S.S.R.) 14, 500-6 (1941)
- 335 VI C Frejacques, Chimie & Industrie 46, 579-79 (1941)
- 336 III B Beachell, Taylor, J. Chem. Phys. 10, 106-10 (1942)
- 337 III B Griffith, Hill, J. Chem. Soc. 1938, 2037-40.
- 338 III B Kondrat'ev, Yakovleva, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 1038-42 (1940)
- 339 III A Kondrat'ev, Magaziner, Chem. Zentr. 1940, II, 2872; J. Phys. Chem. (U.S.S.R.) 14, 6-9 (1940)
- 340 IX B Kondrat'ev, Acta Physicochim. U.R.S.S. 12, No. 5, 637-46 (1940)
- 341 IX A Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 13, 1260-70 (1939)
- 342 III A Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 14, 287-90 (1940)
- 343 III B Nalbandjan, J. Phys. Chem. (U.S.S.R.) 14, 598 (1940)
- 344 IX A Pavlov, Acta Physicochim. 13, 587-90 (1940)
- 345 IX B Pavlov, J. Phys. Chem. (U.S.S.R.) 14, 601-4 (1940)
- 346 III A Semenov, Voronkov, Acta Physicochim. U.R.S.S. 12, 831-78 (1940)
- 347 III B Voronkov, Semenov, J. Phys. Chem. (U.S.S.R.) 13, 1695-1727 (1939)
- 348 III A Bodenstein, Z. Physik. B48, 239-67 (1941)
- 349 III B Bodenstein, Launer, Z. Physik. Chem. B48, 268-88 (1941)
- 350 III B Bodenstein, Zoltan, Math. Nature. Anz. Ungar. Akad. Wiss. 57 613-23 (1938)
- 351 III B Rice, Walters, J. Am. Chem. Soc. 63, 1701-6 (1941)
- 352 V A Dugleux, Laffitte, Compt. Rend. 221, 661-3 (1945)
- 353 III A Fletcher, Rollefson, J. Am. Chem. Soc. 58, 2135-40 (1936)
- 354 III B Bamford, Trans. Faraday Soc. 35, 1239-46 (1939)
- 355 III B Bamford, Bamford, Trans. Faraday Soc. 36, 1036-42 (1940)
- 356 III B Travers, Hawkes, J. Chem. Soc. 1939, 1360-4.
- 357 III B Emeleus, Jolley, J. Chem. Soc. 1936, 1524-9
- 358 IX B Blake, Iredale, Nature 157, 229 (1946)
- 359 IX B Vaidya, Proc. Indian Acad. Sci. 6A, 122-8 (1937)
- 360 III B Bamford, Bamford, J. Chem. Soc. 1941, 30-4.

- 361 III B Lemon, J. Chem. Soc. 1936, 1409-12
362 III B Lowry, J. Chem. Soc. 1937, 1461-8
363 III B Stoddart, J. Chem. Soc. 1939, 5-12
364 III B Murzin, J. Applied Chem. (U.S.S.R.) 17, 370-6 (1944)
365 III B Lewis, Hinshelwood, Chem. Zentr. 1939 I, 2126; Proc. Roy. Soc. (London) A168, 441-54 (1938)
- 366 III C Furman, J. Phys. Chem. (U.S.S.R.) 18, 386-8 (1944)
367 III B Furman, J. Phys. Chem. (U.S.S.R.) 18, 473-6 (1944)
368 III B Briner, Karbassi, Helv. Chim. Acta 28, 1204-11 (1945)
369 III B Appin, Todes, Khariton, J. Phys. Chem. (U.S.S.R.) 8, 866-82 (1936)
370 III B Carter, Travers, Proc. Roy. Soc. (London) A158, 495-8 (1937)
- 371 III B Taylor, Vesselovsky, J. Phys. Chem. 39, 1095-1101 (1935)
372 III B Thompson, Dainton, Trans. Faraday Soc. 33, 1546-55 (1937)
373 III A Steacie, Katz, J. Chem. Phys. 5, 125-30 (1937)
374 III B Steacie, Shaw, Proc. Roy. Soc. (London) A151, 685-93 (1935)
375 III B Purkis, Trans. Faraday Soc. 32, 1466-74 (1936)
- 376 III B Natanson, Acta Physicochim. U.R.S.S. 11, 521-36 (1939)
377 III B Krauss, Saracini, Z. Physik. Chem. A178, 245-54 (1937)
378 III B Shantarovich, Acta Physicochim. U.R.S.S. 2, 665-78 (1935)
379 III B Emeleus, Welch, J. Chem. Soc. 1939, 1928-37
380 III B Yakovlev, Shantarovich, J. Phys. Chem. (U.S.S.R.) 9, 112-31 (1937)
- 381 III A Schenk, Jablonowski, Z. Electrochem. 45, 650 (1939)
382 III B Emanuel, Compt. Rend. Acad. Sci. U.R.S.S. 35, 250-5 (1942)
383 III B Emanuel, Compt. Rend. Acad. Sci. U.R.S.S. 36, 145-9 (1942)
384 III B Emanuel, Acta Physicochim 19, 360-78 (1944)
385 III B Emanuel, J. Phys. Chem. (U.S.S.R.) 19, 15-47 (1945)
- 386 III B Emanuel, Pavlov, Semenov, Compt. Rend. Acad. Sci. U.R.S.S. 28, 618-20 (1940)
387 III B Kondrat'eva, Kondrat'ev, J. Phys. Chem. (U.S.S.R.) 15, 731-8 (1942)
388 III B Kondrat'eva, Kondrat'ev, Compt. Rend. Acad. Sci. U.R.S.S. 31, 128 (1941)
389 III C Brodovich, J. Applied Chem. (U.S.S.R.) 14, 894-9 (1941)
390 III B Allen, Bawn, Trans. Faraday Soc. 34, 463-7 (1938)
- 391 V C Akulov, Compt. Rend. Acad. Sci. U.R.S.S. 43, 301-5; Doklady Akad. Nauk. S.S.S.R. 43, 317-21 (1944)
392 III B Akulov, Doklady Akad. Nauk. S.S.S.R. 39, 239-43 (1943); Compt. Rend. Acad. Sci. U.R.S.S. 39, 224-7 (1943)
393 III B Akulov, Compt. Rend. Acad. Sci. U.R.S.S. 39, 317-21 (1943)
394 III B Akulov, Doklady Akad. Nauk. S.S.S.R. 39, 204-8 (1943); Compt. Rend. Acad. Sci. U.R.S.S. 39, 191-4 (1943)
395 III B Dijksman, Rec. Trav. Chim. 59, 857-71 (1940)
- 396 V B Dijksman, Chem. Weekblad 38, 175-7 (1941)
397 III A Evans, Rushbrooke, Trans. Faraday Soc. 41, 621-9 (1945)
398 III B Von Elbe, J. A. C. S. 59, 970-5 (1937)

- 399 IV B Frank-Kamenetskii, Acta Physicochim. U.R.S.S. 10, 367-70 (1939)
- 400 IV B Zel'dovich, Frank-Kamenetskii, Acta Physicochim. U.R.S.S. 5, 341-50 (1938)
- 401 III A Frank-Kamenetskii, Compt. Rend. Acad. Sci. U.R.S.S. 25, 671-2 (1939)
- 402 XI B Frank-Kamenetskii, J. Phys. Chem. (U.S.S.R.) 13, 738-5 (1939)
- 403 V B Frank-Kamenetskii, Chem. Zentr. 1940 II 3012; J. Phys. Chem. U.S.S.R. 14, 30-5 (1940)
- 404 IV B Frank-Kamenetskii, Acta Physicochim. U.R.S.S. 16, 357-61 (1942)
- 405 IV B Frank-Kamenetskii, Acta Physicochim. U.R.S.S. 20, 729-36 (1945)
- 406 III B Gurney, Arkiv Kemi, Mineral. Geol. 14B, No. 17, 4 pp (1940)
- 407 III A Geib, Z. Elektrochem. 47, 761-5 (1941)
- 408 III A Hulburt, Ind. Eng. Chem. 36, 1012-1017 (1944)
- 409 XI A Jost, Z. Elektrochem. 47, 680-7 (1941)
- 410 IV B Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) 14, 240-5; Acta Physicochim. U.R.S.S. 19, 77-85 (1944)
- 411 I B Meixner, Z. Physik. Chem. B53, 235-63 (1943)
- 412 III B Prettre, Documentation Sci. 6, 71-80 (1937)
- 413 IV A Rice, J. Chem. Physics 8, 727-33 (1940)
- 414 III B Rollefson, J. Phys. Chem. 42, 773-81 (1938)
- 415 IV B Szczeniowski, Rev. Trimestr. Can. 29, 197-209 (1943)
- 416 III B Stupochenko, Chem. Zentr. 1940, II, 2855-6; Acta Physicochim. U.R.S.S. 11, 555-570 (1939)
- 417 III B Semenov, Uspekhi Khim. 5, 321-66 (1936)
- 418 III A Semenov, J. Chem. Phys. 7, 683-99 (1939)
- 419 III A Semenov, Acta Physicochim. U.R.S.S. 18, No. 2-3, 93-147 (1943)
- 420 IV B Todes, Acta Physicochim. U.R.S.S. 5, 785-806 (1936); Chem. Zentr. 1937, II, 2947.
- 421 XI B Todes, Melent'ev, Acta Physicochim. U.R.S.S. 11, 153-80 (1939)
- 422 IV B Melentjev, Todes, J. Phys. Chem. (U.S.S.R.) 14, 1026-42 (1940); Acta Physicochim. U.R.S.S. 14, 27-52 (1941)
- 423 IV B Todes, Acta Physicochim. U.R.S.S. 14, 53-70 (1941)
- 424 III B Todes, Bogutskii, J. Exptl. Theoret. Phys. (U.S.S.R.) 11, 133-9 (1941)
- 425 IV C Blume, Automobiltech Z. 46, 36-9 (1943); Chem. Zentr. 1943, I, 2059
- 426 XI C Broersma, Ing. Nederland.-Indie 8, No. 4, III, 31-8 (1941)
- 427 IX B Boyd, S.A.E. Journal 45, 421-32T (1939)
- 428 IV B Boyd, Withrow, Rassweiler, 11me Congr. Mondiale Petrole 3, Sect. 4, 566-77 (1937)
- 429 III B Boerlage, Broeze, Congr. Chim. Ind. Compt. Rend. 18me Congr. Nancy, Sept.-Oct., 1938, 661-82.
- 430 III B Boerlage, Broeze, J. Soc. Ing. Automobile 13, 135-49 (1939)

- 431 V B Dreyhaupt, Forsch. Gebiete Ingenieurw. 11, 215-23 (1940);
Chem. Zentr. 1941, I, 2079
- 432 IX B Evans, Gas Oil Power 38, 291-2 (1943)
- 433 III B Inogai, Expt. Rept. Impt. Naval Fuel Depot (Japan) 135,
9-96 (1940)
- 434 VI B Jost, Brennstoff u. Wornewirt, 23, 57-62 (1941)
- 435 III B Jost, Von Muffling, Z. Elektrochem. 45, 93-9 (1939)
- 436 IX B Kling, Congr. Chim. Ind. Compt. Rend. 18me Congr., Nancy,
Sept.-Oct., 1938, 251-4
- 437 IX B Kneule, Deut. Kraftfahrtforsch, No. 5, 20 pp. (1938)
- 438 VI C Maurer, Oel. u. Kohle 38, 667-9 (1942)
- 439 VII B Mock, S.A.E. Ann. Meeting 1946, 9 pp.
- 440 III B Newitt, J. Inst. Petroleum 25, 137-48 (1939)
- 441 IV B Schmidt, Muhlner, Forsch. Gebiete Ingenieurw. 13, No. 5, 186-7
(1942)
- 442 VI B Schmidt, Motortech. Z. 5, 41-6 (1943); Chem. Zentr. 1943, II
395-6
- 443 IV B Schmidt, Z. Ver. Deut. Ing. 84, 208-10 (1940)
- 444 IV B Serruys, Pub. Sci. Tech. Ministere Air (France) No. 103,
221 pp (1937)
- 445 IV B Serruys, Congr. Chim. Ind. Compt. Rend. 18me Congr. Nancy,
Sept.-Oct., 1938, 1064-70
- 446 V A Zeise, Z. Elektrochem. 47, 779-800 (1941)
- 447 V A Zeise, Z. Elektrochem 47, 238-62 (1941)
- 448 V B Zinner, Z. Ver. Dent. Ing. 83, 1073-9 (1939)
- 449 VI B Ernst, Deut. Kraftfahrt-forsch. No. 63, 1-20 (1941);
Chem. Zentr. 1943, I, 2657
- 450 IX C Funck, Automobiltech. Z. 45, 21-5 (1942); Chem. Zentr. 1942,
II, 1423
- 451 V B Herele, Forsch. Gebiete Ingenieurw. 10, 15-27 (1939)
- 452 IX B Laure, Pub. Sci. Tech. Ministere Air (France) No. 91, 67-70 (1940)
- 453 IX B Lichtenberger, Seeber, Arch. Tech. Messen 1942, V 8234
- 454 VI D Lonn, Luftfahrt-Forsch 19, 344-6 (1943); Chem. Zentr. 1943
II, 1430
- 455 VI B Rassweiler, Withrow, Cornelius. S.A.E. Journal 46, 25-48 (1940)
- 456 IX B Rothrock, Spencer, Miller, Natl. Advisory Comm., Aeronautics,
Rept. No. 704, 16 pp. (1941)
- 457 V C Scheuermeyer, Steigerwald, Chem. Zentr. 1944, I, 259; Motortech
Z. 5, 229-35 (1943)
- 458 VI B Shoemaker, Gadebusch, Oil Gas J. 44, No. 36, 74-9 (1946)(Jan. 12)
- 459 VI C Sokolik, Yantovskii, Acta Physicochim. U.R.S.S. 19, 329-59 (1944)
- 460 VI B Spencer, Natl. Advisory Comm. Aeronautics Rept. No. 710,
16 pp. (1941)
- 461 V B Starkman, Trans. Am. Inst. Chem. Engrs. 42, 107-20 (1946)
- 462 V B Wolfer, Forsch. Gebiete Ingenieurw. 9, Forschungsheft 392,
15-24 (1938)
- 463 IX B Watts, Lloyd-Evans, Engineering 143, 713-14 (1937)

- 464 V D Widmaier, Deut. Kraftfshrtforsch. No. 63, 21-32 (1941);
Chem. Zentr. 1943, I, 2657
- 465 III C Aten, Kem. Maanedstidsskrift 19, 97-101 (1938); Chem. Zentr. 1938,
II, 2576
- 466 III A Groth, Z. Physik. Chem. Unterricht 52, 157-63 (1939)
- 467 III B Mandala, Chimica e Industria (Italy) 21, 342-5 (1939)
- 468 III B Pearson, Purcell, J. Chem. Soc. 1936, 253-6.
- 469 III A Rice, Teller, J. Chem. Phys. 6, 489-96 (1938)
- 470 III A Rice, Walters, Ruoff, J. Chem. Phys. 8, 259-62 (1940)
- 471 III B Staveley, Hinshelwood, J. Chem. Soc. 1937, 1568-73
- 472 III B Smith, Proc. Roy. Soc. (London) A180, 237-56
- 473 III B Ubbelohde, Chemistry and Industry 1940, 657-9
- 474 III A Waters, Trans. Faraday Soc. 37, 770-80 (1941)
- 475 III B Eucken, Abhandl. Ges. Wiss. Göttingen, Math.-Phys. Klasse.
Folge III, No. 18, 26-36 (1937); Chem. Zentr. 1937 II, 2635
- 476 III A Flock, S.A.E. Journal 49, 332-9 (1941)
- 477 VI A Flock, S.A.E. Journal 49, 332-8 T (1941)
- 478 III A Jost, Angew. Chem. 51, 687-95 (1938)
- 479 III B Lewis, Chem. Rev. 21, 209-11 (1937)
- 480 III B Prettre, Chaleur et Ind. 19, 38-43 (1938)
- 481 III B Stevels, Chem. Weekblad 36, 638-42 (1939)
- 482 III B Stevels, Chem. Weekblad 36, 654-7 (1939)
- 483 III B Steacie, Chem. Revs. 22, 311-402 (1938)
- 484 V B Sokolik, Uspekhi Fiz. Nauk 23, 209-50 (1940)
- 485 III B Sachsse, Angew. Chem. 50, 847-54 (1937)
- 486 VII B Thiemann, Brennstoff-u. Warmewirt 24, 29-32; Chem. Zentr. 1942,
485
- 487 III A Wittig, Angew. Chem. 52, 89-96 (1939)
- 488 V B Berger, Feuerschutztech. 21, 127-30, 146-9, 157-9 (1941);
Chem. Zentr. 1942, I, 907-8
- 489 IX A Vaidya, J. Sci. Ind. Research (India) 3, 149-58 (1944)
- 490 IX B Kondrat'ev, Uspekhi Khimii 12, 308-17 (1943)
- 491 IX A Kondrat'ev, Akad. Nauk S.S.S.R., Inst. Khim. Fiz. Moskva 1944,
80 pp.
- 492 IX A Czerlinsky, Seibt, Luftfahrt-Forsch 15, 316-20 (1938)
- 493 IX B Guest, U. S. Bur. Mines Rept. Invest. 3753 (1944)
- 494 III B Landau, Chem. Rev. 21, 245-58 (1937)
- 495 V A Linnett, Raynor, Frost, Trans. Faraday Soc. 41, 487-98 (1945)
- 496 IX B Jorissen, Snijders, Vink, Rec. Trav. Chim. 59, 957-62 (1940)
- 497 IV B Mole, Proc. Phys. Soc. (London) 48, 857-64 (1936)
- 498 IX A Paterson, Phil. Mag. 28, 1-23 (1939)
- 499 V B Paterson, Phil. Mag. 30, 437-57 (1940)
- 500 V B Schade, Naturwissenschaften 25, 568-9 (1937)
- 501 III A Semenov, Uspekhi Fiz. Nauk 23, 251-92 (1940)
- 502 IV B Silver, Phil. Mag. 23, 633-57 (1937)
- 503 V B Vaillard, J. Chim. Phys. 40, 54-61 (1941); Chem. Zentr. 1943,
II, 1441

- 504 V B Vaillard, J. Chim. Phys. 40, 101-8 (1943)
- 505 V B Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) 9, 1530-4 (1939)
- 506 IV B Coward, Payman, Chem. Revs. 21, 359-66 (1937)
- 507 IV B Coward, Hartwell, Georgeson, J. Chem. Soc. 1937, 1482-9
- 508 IV C Dicent, Shchelkin, Acta Physicochimica U.R.S.S. 19, 302-12 (1944)
- 509 IV B Denues, J. Am. Chem. Soc. 63, 1757-8 (1941)
- 510 IV B Damkohler, Z. Elektrochem. 47, 547-67 (1941)
- 511 IV B Flock, Marvin, Caldwell, Roeder, Natl. Advisory. Comm. Aeronaut., Rept. No. 682, 20 pp (1940)
- 512 XIII C Flock, Scientific Monthly, 52, 216-32, 349-58 (1941)
- 513 IX B Flock, Marvin, Chem. Revs. 21, 367-87 (1937)
- 514 IV B Jost, Muffling, Z. Physik Chem. A181, 208-14 (1937); Chem. Zentr. 1938, II, 1176
- 515 IX B Khitrin, Tech. Phys. U.S.S.R. 4, 110-20 (1937)
- 516 IX B Kolesnikova, J. Tech. Phys. (U.S.S.R.) 11, 649-53 (1941)
- 517 IV B Kolodtsev, Tech. Phys. U.S.S.R. 3, 1034-43 (1936)
- 518 III B Lewis, Von Elbe, Chem. Rev. 21, 347-58 (1937)
- 519 IV A Lewis, Von Elbe, J. Applied Phys. 10, 344-59 (1939)
- 520 IV B Mache, Hebra, Sitzber, Akad. Wiss. Wien. Math-naturw. Klasse, Abt. 11a, 150, 157-74 (1941)
- 521 I B Manson, Compt. Rend. 219, 408-9 (1944)
- 522 IX B Malinovskii, Physik. Z. Sowjetunion 9, 264-7 (1936)
- 523 IV B Smith, Chem. Revs. 21, 389-412 (1937)
- 524 IV B Townend, Maccormac, Inst. Gas. Engrs., Commun. No. 221, 14 pp; Gas World 111, 354-6 (1939)
- 525 IV B Van de Poll, Westerdijk, Z. Tech. Physik 22, 29-32 (1941)
- 526 III A Zel'dovich, Semenov, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 1116-23 (1940)
- 527 IV B Becker, Z. Elektrochem. 42, 457-61 (1936)
- 528 IX B Broersma, J. Aeronaut. Sci. 8, 62-72 (1940)
- 529 VI A Jost, Z. Physik, Chem. B42, 136-42 (1939)
- 530 III A Jost, Muffling, Z. Physik. Chem. A183, 43-54 (1938)
- 531 XI B Laffitte, II^{me} Congr. mondial petrole 3, Sect. 4, 738-43 (1937)
- 532 I B Manson, Compt. Rend. 218, 29-31 (1944)
- 533 IV B Pfriem, Forsch. Gebiete Ingenieurw. 12, 143-58 (1941); Chem. Zentr. 1941, II, 2645-6
- 534 IV A Reingold, Cahiers Phys. 10, 43-54 (1942)
- 535 IV B Shtsholkin, Compt. Rend. Acad. Sci. U.R.S.S. 23, 636-40 (1939)
- 536 IV B Tokarev, Nekrasov, J. Phys. Chem. (U.S.S.R.) 14, 513-20 (1940)
- 537 IV B Thomas, J. Chem. Phys. 12, 449-53 (1944)
- 538 IV B Veron, Compt. Rend. 207, 1037-9 (1938)
- 539 IV B Veron, Chaleur et Ind. 20, 59-93 (1939)
- 540 IV B Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) 12, 389-406 (1942)

541 XI A Zel'dovich, Ratner, J. Exptl. Theoret. Phys. (U.S.S.R) 11,
170-83 (1941)
542 XI B Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) 10, 542-68 (1940)
543 IX B Zouckermann, Heyberger, Compt. Rend. 209, 680-2 (1939)
544 IV A Behrens, Naturwissenschaften, 32, 299-300 (1944)
545 IV A Garside, Forsyth, Townend, J. Inst. Fuel 18, 175-86 (1945)

546 IV B Khitrin, Tech. Phys. U.S.S.R. 4, 121-37 (1937)
547 IV A Lewis, Von Elbe, J. Chem. Phys. 11, 75-97 (1943)
548 IV A Von Elbe, Mentser, J. Chem. Phys. 13, 89-100 (1945)
549 IV B Vasilescu, Am. Phys. 18, 190-208 (1943)
550 IX A Wolfhard, Z. Physik 112, 107-28 (1939)

551 IV B Cowling, Phil. Mag. 33, 61-7 (1942)
552 V B Dreyhaupt, Motortech. Z. 4, 333-9 (1942); Chem. Zentr. 1943,
I, 355-6
553 IV B Dreyhaupt, Motortech. Z. 5, 53-9 (1943); Chem. Zentr. 1943,
I, 2657
554 IV A Dankohler, Z. Elektrochem. 46, 601-26 (1940)
555 IV B Shvab, J. Tech. Phys. (U.S.S.R.) 11, 431-42 (1941)

556 IV B Shchelkin, J. Tech. Phys. (U.S.S.R.) 18, 520-30 (1943)
557 III B David, Nature 138, 930 (1936)
558 IX B David, Phil. Mag. 23, 251-6 (1937)
559 IV B David, Phil. Mag. 23, 345-55 (1937)
560 IV B David, Engineering 144, 531-3 (1937)

561 IX B David, Engineering 149, 241-2 (1940)
562 IV B David, Pugh, Nature 145, 896-7 (1940)
563 IV B David, Leak, Pugh, Phil. Mag. 31, 156-68 (1941)
564 IV B David, Nature 147, 89 (1941)
565 IX B David, Engineer 171, 268-70 (1941)

566 IV B David, Nature 150, 320-1 (1942)
567 IV B David, Mann, Nature 150, 521-6 (1942)
568 III A David, Mann, Nature 151, 392 (1943)
569 IV B David, Mann, Phil. Mag. 34, 816-22 (1943)
570 IV B David, Mann, Nature 154, 115 (1944)

571 IV B Leah, Nature 145, 897-8 (1940)
572 IV B Lewis, Von Elbe, J. Chem. Phys 7, 197-8 (1939)
573 IV B Zeise, Z. Elektrochem. 47, 172-7 (1941)
574 IX A Bosanquet, J. Inst. Fuel 12, 14-17S (1939)
575 IX B Eggert, Bonhoeffer, Z. Angew. Phot. 1, 43-7 (1939)

576 IX A Von Elbe, J. Applied Phys. 11, 698-706 (1940)
577 IX A Fishenden, Saunders, J. Inst. Fuel 12, 5-14S (1939)
578 IX B Hase, Z. Ver. Deut. Ing. 81, 571-5 (1937)
579 IX A Matthews, J. Inst. Fuel 12, 72-5S (1939)
580 IX B Meissner, Forsch. Gebiete Ingenieurw. B9, 213-19 (1938)
581 IX B Pirani, Trans. Electrochem. Soc. 69, 417-431 (1936)
582 IX A Ribaud, Laure, Rev. Optique 19, 123-34, 220-1 (1940)

- 583 IX B Ribaud, Laure, Gaudry, J. Inst. Fuel 12, 18-30S (1939)
- 584 IX A Richardson, Brit. Coal. Utilization Research Assoc. Bull. 2, 165-71 (1945)
- 585 IX B Schroder, Motortech. Z. 1, 181-90; 2, 7-15 (1940); Chem. Zentr. 1940, 1, 3734.
- 586 IX A Swallow, J. Inst. Fuel 12, 68-72S (1939)
- 587 IX B Tewes, Z. Tech. Physik 22, 160-7 (1941)
- 588 IX B Brinkman, Nederland. Tijdschr. Natuurkunde 7, 65-85 (1940)
- 589 IX A Coheur, F., Coheur, P., Rev. Universelle Mines 19, 86-9 (1943); Chem. Zentr. 1944, I, 978.
- 590 IX B Graff, Luftfahrt-Forsch. 18, 8-17 (1941); Chem. Zentr. 1941, II, 3269
- 591 IX A Knauss, McCay, Phys. Rev. 52, 1143-50 (1937)
- 592 IX B Kobayashi, Trans. Soc. Mech. Engrs. (Japan) 3, 192-7 (1937)
- 593 IX A Larsen, Siddall, Heindhofer, J. Inst. Fuel 12, 55-6S (1939)
- 594 IX A Schack, J. Inst. Fuel 12, 30-8S (1939)
- 595 IX B Severinghaus, Mech. Eng. 59, 334-358 (1937)
- 596 IX B Swart, Het. Gas. 56, 147-9 (1936)
- 597 IX A Thring, J. Inst. Fuel 12, 58-61S (1939)
- 598 IX A Zhukovskii, Tech. Phys. U.S.S.R. 5, 968-94 (1939)
- 599 IX B David, Engineer 172, 186-7 (1941)
- 600 IX B Van de Poll, Westerdiijk, Compt. Rend. 209, 158-60 (1939)
- 601 IX B Rosenthal, Arch. Tech. Messen Lfg. No. 127, T2-3, 4 pp (1942); Chem. Zentr. 1942, I, 3236.
- 602 IX B Yosida, Rept. Aeronaut. Research Inst., Tokyo, Imp. Univ. 14, 195-209 (1939)
- 603 IX B Graff, Z. Ver Deut. Ing. 86, 461-6 (1942)
- 604 IX B Naeser, J. Inst. Fuel 12, 38-41S (1939)
- 605 IV B Uyehara, Myers, Watson, Wilson, Trans. Am. Soc. Mech. Engrs., 68, 17-28, Discussion 28-30 (1946)
- 606 IX A Leah, Nature 152, 303-4 (1943)
- 607 IX B Leah, Philosophical Magazine 34, 795-803 (1943)
- 608 I B Matthews, Hurd, Trans. Am. Inst. Chem. Engrs. 42, 55-78 (1946)
- 609 I B Rossini, Knowlton, J. Research Natl. Bur. Standards 19, 249-62 (1937)
- 610 I B Rossini, Knowlton, J. Research Natl. Bur. Standards 19, 339-45 (1937)
- 611 I B Wartenberg, Nachr. Ges. Wiss. Göttingen, Math.-Physik Klasse, Fachgruppe III, N.F. 1, No. 19, 193-3 (1937)
- 612 I B Coops, Mulder, Dienske, Smittenberg, Rec. Trav. Chim. 65 128 (1946)
- 613 I B Jessup, J. Res. Natl. Bur. Standards 18, 115-28 (1937)
- 614 I B Pitzer, Chem. Rev. 21, 59-57 (1940)
- 615 I A Zeise, Z. Elektrochem. 48, 693-714 (1942)
- 616 I B Zeise, Khodschanian, Feuerungstech 28, 54-6 (1940)
- 617 I B Zeise, Z. Elektrochem. 43, 704-8 (1937)

618	I	B	Burke, Hunt, J. Phys. Chem. <u>45</u> , 1346-59 (1941)
619	I	B	Benedict, J. Chem. Phys. <u>10</u> , 747-58 (1942)
620	I	B	Hottel, Eberhardt, Chem. Revs. <u>21</u> , 438-60 (1937)
621	I	B	Pitzer, J. Chem. Phys. <u>5</u> , 469-72 (1937)
622	I	B	Rossin, Fehling, J. Inst. Fuel <u>16</u> , No. 86, 20-25 (1942)
623	I	C	Von Stein, Forsch, Gebiete Ingenieurw. <u>14</u> , 113-23 (1943)
624	IV	B	Walker, Phil. Mag. <u>34</u> , 486-88 (1943)
625	IV	C	Walker, Phil. Mag. <u>35</u> , 680-5 (1944)
626	I	A	Wiebe, Shultz, Porter, Ind. Eng. Chem. <u>34</u> , 575-80 (1942)
627	IV	B	Withrow, Cornelius, S.A.E. Journal <u>47</u> , 526-48 T (1940)
628	I	B	Zeise, Feuerungstech. <u>26</u> , 145-8 (1938)
629	XII	B	Kuhn et al, Chemical Eng. News <u>23</u> , 1516-22, Sept. 10, 1945
630	XII	B	Bellinger, Friedman, Bauer, Eastes, Ladd, Ross, Ind. Eng. Chem. <u>38</u> , 160-9 (1946)
631	XII	B	Lawrence, Mech. Eng. <u>68</u> , 615-617 (1946)

Little, Arthur D.

DIVISION: Guided Missiles (2)

SECTION: Propulsion (5)

CROSS REFERENCES: Propellants, Solid (75457); Propellants, Liquid (75455.5); Combustion (23600)

U

ATI- 499

ORIG. AGENCY NUMBER

 Rumblebee Rpt.
No. 47

REVISION

AUTHOR(S)

AMER. TITLE: A summary of the status of research on the mechanism of combustion

FORG'N. TITLE:

LITTLE, ARTHUR D. INC.

ORIGINATING AGENCY: Johns Hopkins Univ., Applied Physics Lab., Silver Spring, Md.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N CLASS	U. S. CLASS	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	Oct '46	63		

ABSTRACT

Research is conducted on the hydrogen-oxygen reaction; combustion of carbon monoxide; oxidation of hydrocarbons; oxidation of aldehydes, ketones, ethers, and alcohols; combustion of formic acid; peroxide formation and decomposition; theory of chemical kinetics; studies of physical aspects of combustion; and thermodynamic studies. Results of the research as to mechanisms of combustion on the various compounds are given. Summary of rocket propulsion compounds used for jet propulsion in Germany is given.

* Combustion

FORM 10 (10-1-57)
Little, Arthur D.

DIVISION: Guided Missiles (1)
SECTION: Propulsion (3)
CROSS REFERENCES: Propellants, Solid (75457); Propellants, Liquid (75455.5); Combustion (23600)

ATI- 499

ORIG. AGENCY NUMBER

Rumblebee Rpt.
No. 47

REVISION

AUTHOR(S)

ABSTRACT TITLE: A summary of the status of research on the mechanism of combustion

FOOTNOTES:

ORIGINATING AGENCY: Johns Hopkins Univ., Applied Physics Lab., Silver Spring, Md.

TRANSLATION

COUNTRY	LANGUAGE	FOOTNOTES	U. S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	Oct '46	63		

ABSTRACT

Research is conducted on the hydrogen-oxygen reaction; combustion of carbon monoxide; oxidation of hydrocarbons; oxidation of aldehyde, ketones, ethers, and alcohols; combustion of formic acid; peroxide formation and decomposition; theory of chemical kinetics; studies of physical aspects of combustion; and thermodynamic studies. Results of the research as to mechanism of combustion on the various compounds are given. Summary of rocket propulsion compounds used for jet propulsion in Germany is given.